ALLIS-CHALMERS

Electrical Review

Fourth Quarter, 1951

LOW VOLTAGE JITTERS on heavily loaded feeders vanished when pole-type regulators were developed. They are suitable for both urban and rural distribution lines. Motors last longer; electrical home and farm appliances work properly; illumination improves. Introduced less than two years ago, thousands of pole-type units are scheduled for installation during 1952.

These three 50-amp regulators are helping a southern utility meet its growing and fluctuating load. Seasonal demands of seven local cotton gins and electric house heaters during cold spells caused a critical low-voltage condition until these regulators were installed. Units provide ± 10-percent regulation in 32 5/8-percent steps.

Allis-Chalmers Staff Photo

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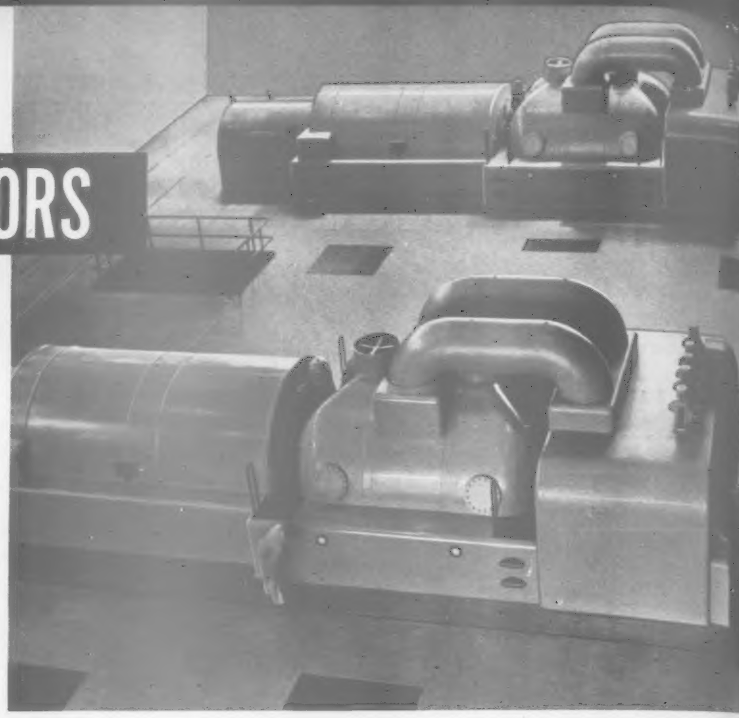
ROTATING REGULATORS *Control* Systems Reactive Current



PARALLEL GENERATORS require careful division and control of their reactive load. While reactive or wattless current produces no real power, it can create serious heat losses in lines, transformers, and generators.

by T. B. MONTGOMERY
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System generating units and large synchronous machines are now controlled in relation to entire generating system.

TODAY'S GENERATOR VOLTAGE regulator is more than the term implies. It serves as a co-ordinating device for tying one generator into a generating system. The modern regulator assures proper division of reactive load, prevents the generator under control from being overloaded with wattless current, and eliminates the dropping of generator load due to improper excitation. It also compensates for voltage drop in lines and transformers.

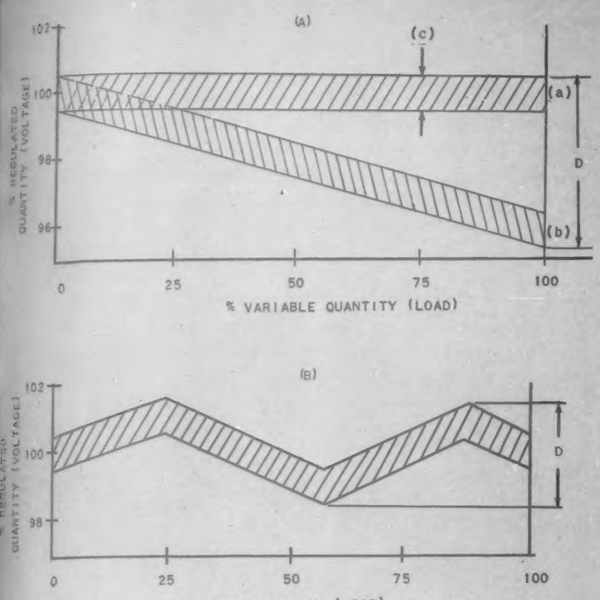
In its general concept, regulation means the control or holding of a quantity such as voltage, speed, current or any other quantity that can be measured electrically. With voltage regulators the quantity voltage is regulated to remain fixed or to vary as a function of other quantities. The characteristics of regulators with respect to the quantity regulated fall into two classes as shown in Figure 1.

A regulator is known as astatic when the regulated quantity remains constant and independent of the variable quantity. This is represented graphically at (a) in Figure 1(A). A regulator is called static when the regulated quantity acquires different values dependent upon the variable quantity. This condition is shown at (b), Figure 1(A). Both of these characteristics have a definite place in regulator operation.

All regulators require some change in the regulated quantity to initiate action. The sensitivity of the measuring element is the amount of change required in the regulated quantity before regulator action is initiated. In mechanical regulators, the sensitivity is dependent on the friction in the device; in regulators without moving parts it is dependent on the "trigger action" or the steepness of the characteristic of the sensing unit. In a graph such as Figure 1(A) the band of insensitivity is represented by the width (c) of the regulator characteristic line. A specification will often read, "The regulator is to have a sensitivity of plus or minus one percent." What is meant is that the regulator is allowed to have an insensitivity range of two percent or plus or minus one percent from the mean. Most modern regulators for large alternating current machines have a sensitivity within plus or minus one-half of one percent.

The term sensitivity is often confused with accuracy. The inaccuracy is the total variation of the regulated quantity over the entire regulating range. This is represented by D Figure 1(A) and would include any static droop which might purposely be designed into the regulator. If the regulator characteristic should include irregularities as shown at Figure 1(B), the inaccuracy includes the overall band of all such variations. It is therefore obvious from Figure 1(A) that with an astatic regulator, as represented by band (a), the sensitivity and accuracy are the same. That is why this characteristic is preferred on voltage regulators and altered only when required to accomplish control functions.

The astatic characteristic (a) in Figure 1(A) which gives the best accuracy is inherently the most unstable. A small change in the regulated quantity unbalances the regulator producing a corrective signal until the regulated quantity is returned to its correct value. With a perfectly astatic regulation curve, a small change in the regulated quantity would produce a 100-percent change in the variable quantity. Obviously,



ACCURACY AND SENSITIVITY are often confused. The accuracy is affected by static droop designed into the regulator but sensitivity is affected only by the change required before regulation begins. **(FIG. 1)**

therefore, when regulators are designed to give the best accuracy, other means such as damping and stabilizing circuits are necessary to give stability.

In contrast, the static characteristic (b), Figure 1(A) is inherently stable as a small change in the regulated quantity gives a relatively small change in the variable quantity. As the regulator moves over its operating range, the value of the regulated quantity at which it balances is changed. Normally, this value droops with increase in load.

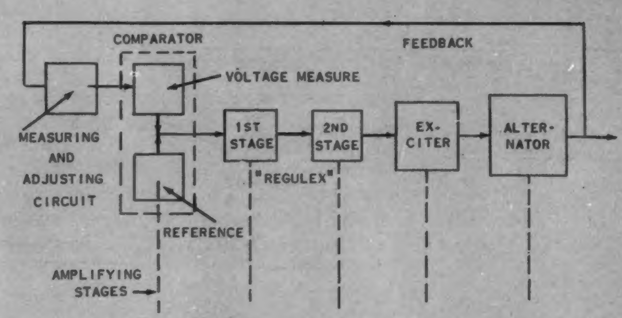
In the *Regulex* voltage regulating scheme the regulator is part of a closed-cycle system as shown schematically in Figure 2. In this system a measure of the alternator output voltage is fed back through the measuring and adjusting circuit and is amplified through the five stages consisting of the comparator, the two *Regulex* exciter stages, the main exciter and the alternator.* The system operates to control the alternator output voltage.

With the high gain or amplification from the comparator to the main exciter, a very slight deviation from the balance point of the comparator gives a trigger action to change the main exciter voltage from the no load to the full load point. Thus the small deviation in the regulated voltage required to give full regulator action establishes the astatic regulator characteristic under straight voltage control as shown at (a), Figure 1(A).

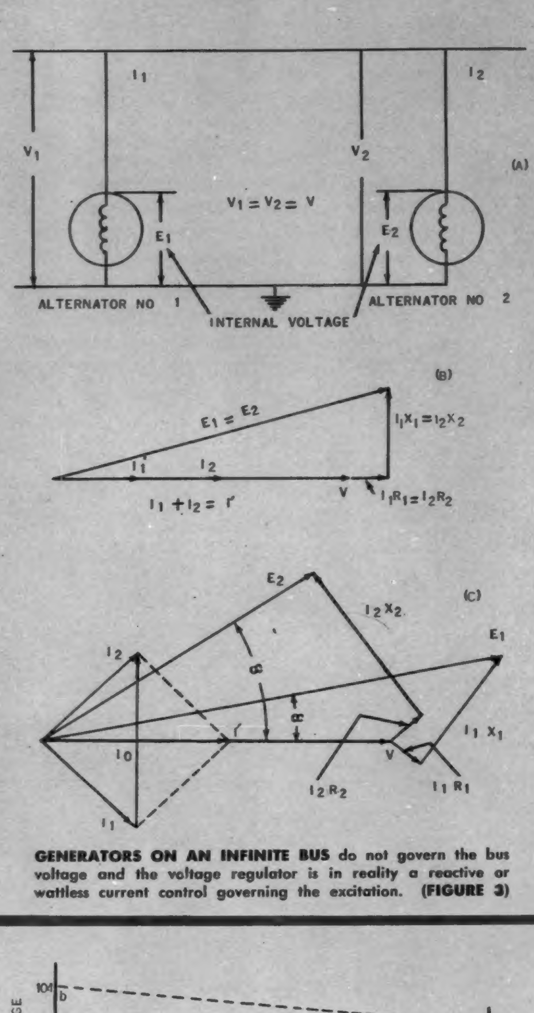
The factors in operation that make it necessary to diverge from straight voltage regulation are as follows:.

1. Reactive current compensation with parallel operation of alternators.
2. Line and transformer drop compensation.
3. Current limit and thermal protection for synchronous condensers.
4. Minimum excitation limit for synchronous condensers and stability control of generators.

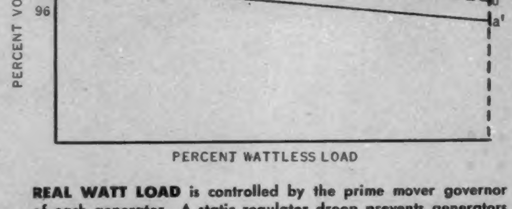
* *Five Stages to Stability,* Montgomery, T. B., and Timm, H. D., Allis-Chalmers *Electrical Review,* Third Quarter, 1951.



ASTATIC CHARACTERISTICS of a closed cycle voltage regulator are modified with a static droop or rise for the additional functions required of modern regulators. **(FIGURE 2)**



GENERATORS ON AN INFINITE BUS do not govern the bus voltage and the voltage regulator is in reality a reactive or wattless current control governing the excitation. **(FIGURE 3)**



REAL WATT LOAD is controlled by the prime mover governor of each generator. A static regulator droop prevents generators from taking more than their share of wattless load. **(FIGURE 4)**

Regulators control wattless power

When an accurate voltage regulator controls the excitation of an alternator connected in parallel with other regulated machines, regulator operation controlling the alternator field has no appreciable effect on the real or kilowatt load. The real load is adjusted by changing torque on the alternator shaft and is controlled by the action of the speed governor on the prime mover. Changes in field excitation under the action of voltage regulators affect only the reactive or wattless component of the alternator output.

The wattless component in any power system is the excitation required for synchronous and induction machines and magnetic circuits such as solenoids on the system. The ac alternator, unlike the self-excited dc generator, does not necessarily supply the correct self-excitation for the voltage delivered at its terminals. If it is under-excited it draws a leading current from other alternators or capacitors on the system. This current is leading when viewed from this machine, but is lagging when viewed from the position of the other machines on the system which supply it. The amount of this leading current represents the deficiency of the alternator to supply its own required excitation.

If the machine is over-excited, it supplies both its own excitation and wattless power required for the excitation, or magnetization, of other apparatus on the system which cannot or does not supply its own exciting current.

This can be explained further by reference to Figure 3. Figure 3(A) shows a single line diagram of two duplicate alternators operating in parallel on an infinite bus and Figure 3(B) shows their vector relations at unity power factor with reference to the external circuit. An infinite bus is one fed by a power system sufficiently large that the bus voltage will not be changed appreciably by the individual generators connected to it. In this diagram the alternator reactances x are assumed equal and E_1 and E_2 are considered as the internal induced electromotive forces.

In this parallel circuit with the external voltage V held constant by other generators on the system V_1 and V_2 are equal. I_1R_1 and I_2R_2 are equal since the currents are assumed to be equal. I_1 and I_2 add up to the in-phase current I′ delivered by the two machines. Voltage regulators control the excitation of both alternator No. 1 and alternator No. 2.

It is not practical to set two voltage regulators to hold identically the same voltage and keep the setting under all conditions without equalizing means. The case is similar to the equalizing required between two compound wound dc generators in parallel or between two speed governors controlling the power to two prime movers.

If, for example, these two units with equal regulator settings are put on the line at the same time and the heating of the elements of one regulator is faster than that of the other, it will temporarily try to regulate for a higher voltage, and will move its excitation to a maximum. The resulting condition is shown vectorially in Figure 3(C) and a circulating current I_0 will flow between machines, leading in machine No. 2 and lagging in machine No. 1. Although it produces no real power I_0 causes unnecessary heating of the machine because I_1 and I_2 must be larger to give the same total value I′ which is the summation of the currents in both machines in phase with the terminal voltage V.

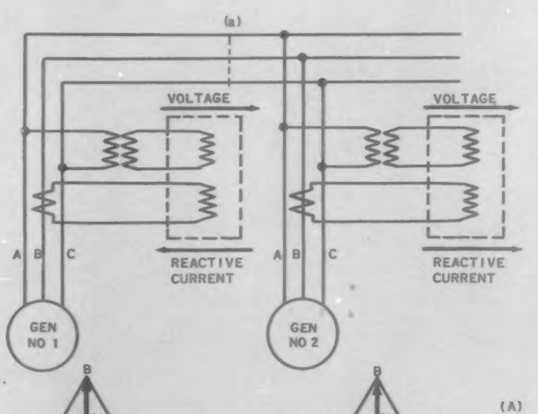
Static droop provided

To prevent circulating current between the two machines without equalizing means when both generators are under regulator control, the alternator is given a static voltage droop with increased reactive load. Referring to Figure 1(A) the regulator is made to function according to characteristic (b) where the regulated quantity is voltage and the variable quantity is reactive or wattless load.

Regulator literature is confusing when referring to a voltage droop with the condition where a generator under voltage regulator control is tied to a system. Normally, the voltage cannot be made to vary substantially by means of the regulator because the capacity of one generator is usually small compared to the whole system. Under system operation, the term droop is only illustrative, because, as explained by Figure 3 the change of excitation by the regulator is a regulation of the 90 degrees or wattless current. Actual voltage regulation is obtained only when a generator is not connected to a system.

A better understanding of this point can be obtained by reference to Figure 4. In this figure voltage is plotted against wattless current. Suppose the regulator is given a four-percent droop with wattless current. If the regulator could change system voltage, increase in wattless current would drop the voltage from 100 percent at no load along the line a-a′. If the regulator voltage setting is raised four percent by means of the voltage adjusting rheostat from 100 percent at no load, the voltage line is moved from a-a′ to b-b′ and 100-percent wattless load is picked up at point b′. In this change the system voltage remains on line a-b′.

Furthermore under ideal conditions, if 100-percent voltage is obtained at no load and the real or watt load is increased by throttle opening, watt current is picked up and the locus of operation in Figure 4 is from a to c in going from 0 to 50-percent watt load. In this case, as watt load is increased from zero, the generator will start to draw a leading current from



CIRCULATING CURRENTS between generators connected to an infinite bus are virtually eliminated by reactive current compensators in the generator voltage regulators. **(FIGURE 5)**

the system due to under-excitation. The reactive compensation will act in the boost direction to keep the regulator substantially astatic from a to c. At point c automatic regulator operation is along line c-d.

If at point c with 50-percent watt load the regulator voltage setting is increased such as to make the generator assume full rated kva load, the regulator characteristic changes from c-d to b-b′. Under this condition, the generator has 50-percent wattless current and 50-percent watt current, with a drooping characteristic with increased wattless and a rising characteristic with a decrease in wattless for parallel operation.

Therefore it is important to note that, with a voltage regulator in operation on a generator, the control is *Astatic* with real load and *Static* with reactive or wattless load.

Further understanding of reactive load division between generators when the generators are under the control of regulators and are connected to an infinite bus, is given by a consideration of the three-phase relations as pictured in Figure 5. The point of view should be directed from (a) from which point the circulating current I_0 as explained under Figure 3 is leading in generator No. 1 and lagging in generator No. 2. In this figure a simple regulator is shown with the single-phase voltage control taken from phase AC and the reactive current measurement taken from current transformers in line B. The three-phase voltage and current relations are shown at Figure 5(A) for the two machines, and the reactive component I_0 adds to the voltage of regulator No. 2 and subtracts from the voltage of regulator No. 1. Under automatic control in a closed-cycle system the voltage applied to regulator No. 2 would appear too high because the reactive component adds to the voltage and the regulator would move to reduce excitation. Similarly, the voltage applied to regulator No. 1 would appear too low and the regulator would move to increase excitation. Referring to Figure 3(C) the circulating current I_0 will be reduced to a minimum, both machines will carry equal share of reactive current, and the condition of Figure 5(B) will prevail.

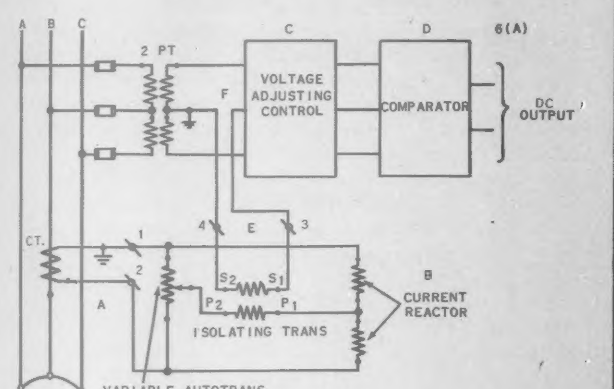
When used with the *Regulex* voltage regulator the device used to accomplish reactive current division is known as the reactive current compensator.

Generators share load

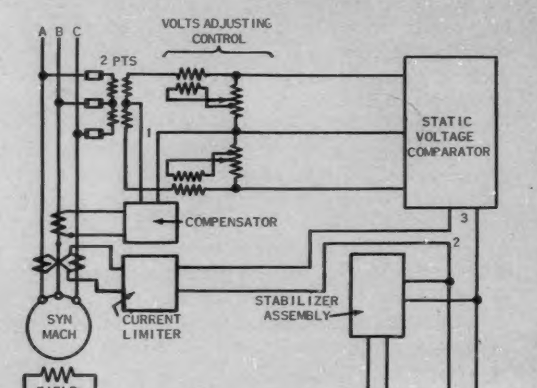
The reactive current compensator consists of a bridge between a high impedance autotransformer (A) and two low impedance reactors (B) as shown by Figure 6(A). Its output is inserted in the center leg of the three phase open delta circuit between the voltage measuring potential transformers and the voltage adjusting control (C). The isolating transformer allows independent grounding of the potential and current transformers. The compensator as applied to the regulating system is also shown at (1) in Figure 7.

The voltage and current relations at the synchronous machine terminals are shown in Figure 6(B) and the current OX measured by the current transformer consists of the in-phase component OB and the reactive component OB′. At unity power factor when the reactive component OB′ is zero, the current is represented by the vector OB only. When the sum of these components is translated to voltages of the proper magnitude by the autotransformer, reactors, and isolating transformer and inserted in the comparator circuit the effect is to vectorially add to or subtract from the AB and BC sides of the three phase voltage triangle and thereby change the three phase voltage to the comparator.

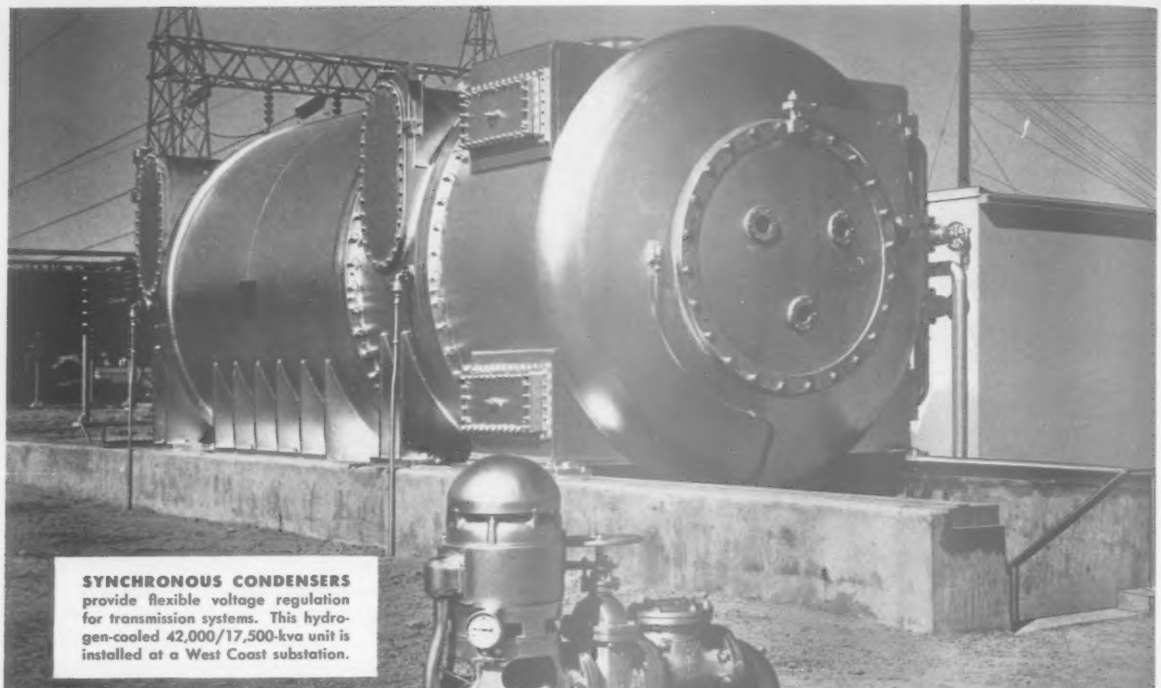
It is characteristic of current transformers that the current in the secondary is a true measure of the current in the primary, and that the current in the secondary is directly in phase with the primary current. However, the voltage in the current transformer secondary depends on the impedance of the load in its



VARIABLE AUTOTRANSFORMER provides a manual control of compensation. The compensator modifies the voltage adjusting control either increasing or decreasing its signal. **(FIGURE 6)**



REACTIVE LINE DROP COMPENSATOR operates the same as the reactive current compensator except that the output signal of the compensator is reversed. **(FIGURE 7)**



SYNCHRONOUS CONDENSERS provide flexible voltage regulation for transmission systems. This hydrogen-cooled 42,000/17,500-kva unit is installed at a West Coast substation.

secondary circuit. In this case the current through the compensator at unity power factor is in phase with the current OB. However, the voltage 1-2 and also P1-P2 which is applied across the isolating transformer from a purely reactive current transformer secondary load, leads the current by 90 degrees. As shown in Figure 6(C) the compensating voltage at unity power factor with full load current when inserted in the comparator circuit at (F) appears as BE_0. At unity power factor, addition of vector BE_0 has no effect on the comparator because, within the limits of operation, as AE_0 is decreased below the no load voltage AB, CE_0 is increased correspondingly above CB and the average three-phase voltage remains substantially the same. The reactive or wattless component will produce a voltage which lags the vector BE_0 by 90 degrees and causes it to rotate clockwise as the power factor decreases from unity in the lagging direction. At zero power factor lagging it will have the position BE_L and the wattless component will add directly to the average three phase voltage. The resultant voltages transmitted to the comparator at (F) ahead of the voltage adjusting control (c) are AE and CE at normal load power factor and the overall increase in voltage is proportional to reactive current only.

Normally, not more than five percent droop with increased wattless current is required at full load to cause adequate division of wattless current between alternators. The voltage BE is approximately five percent of the three-phase voltages measured by the potential transformers. The vector proportions shown in Figure 6(C) are exaggerated for the sake of clarity.

With the comparator adjusted for a certain voltage, the addition of voltage BE, Figure 6(C), measured from and in proportion to reactive load, makes the comparator voltage too high for its adjustment, and it instigates an output to reduce excitation. This provides a decrease in the machine internal voltage with increase in reactive current and gives the regulator a droop with increase in lagging wattless current. Thus two or more generators can be made to operate in parallel with proper division of reactive current in proportion to their capacities.

Line and transformer drops minimized

When a generator is operating on a power system, it is often desired to keep a constant voltage at a distribution point some distance from the generator. With transformers between the generator and the distribution center, the generator voltage must increase with load current to overcome the reactive and resistance drop of the transformers and the line. The voltage relations with reactive load are shown in Figure 8(A) where the voltage E_1 is required from the generator to overcome the resistance and reactive drops RI and XI respectively and maintain the voltage E_2 at the load center. With a regulator in operation from the generator terminals, the distribution center voltage E_2 can be maintained constant under all conditions. Both the RI and the XI drops can be compensated for if required, but in most cases the RI drop is small enough to be neglected and the XI drop only need be considered.

The reactive line drop compensator is a mechanical and electrical duplicate of the reactive current compensator used for division of reactive load between alternators in parallel. The only difference required is that the generator be given a rising voltage characteristic with increasing reactive load rather than a drooping characteristic as is the case with alternators in parallel.

The rising voltage characteristic is accomplished by the simple expedient of reversing the compensator output as applied to the comparator by reversal of the outgoing leads

connected to terminals 3 and 4 as shown at E in Figure 6. When applied to the measured voltage with this connection the compensator action reduces the three phase average voltage (ABC) which is presented to the comparator to AEC. This is illustrated at B, Figure 8.

Considering that the regulator is adjusted with a definite setting, an increase in reactive load will make the voltage to the comparator appear too low. The value of the voltage reduction will be a measure of the XI drop in Figure 8(A). The comparator will produce an output to raise the generator voltage to the value E_1, Figure 8(A), giving the voltage E_2 at the distribution center.

The above description is practical with one machine in a station where it is only necessary to compensate for the drop between its terminals and the distribution center. If there are two or more machines in a station, there must be reactive compensation for proper parallel operation between alternators and in addition the bus voltage must be given a rising characteristic to overcome drop between the machines and the distribution center.

When parallel operation and line drop compensation are both required in a station one means of connecting the compensators is shown in Figure 9. The reactive current compensators are connected at the machine terminals as shown at A. The line drop compensator measuring the combined reactive current from the two machines is shown at B. The output from the line drop compensator and the reactive current compensators are connected in series to effect the respective comparators at the voltage adjusting controls.

The line drop compensator gives an equal voltage rise to each machine with increased reactive current to maintain the correct voltage at the feeder, or to the distribution point by compensating for line and transformer drops. Equal division of reactive current between alternators is maintained by the reactive current compensators.

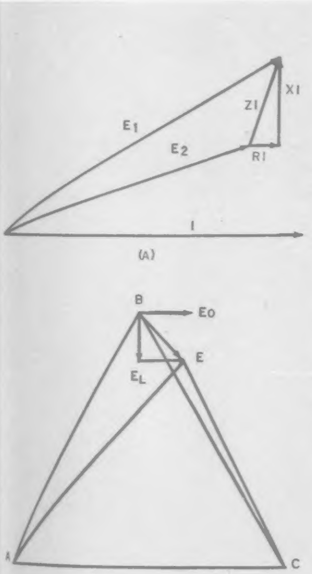
Synchronous machines give and take

A synchronous motor can operate with an excitation voltage which is greater or less than the applied voltage. In many texts this is called the internal voltage because it can be conveniently represented by vectors which may be used to give the electrical dimensions of the machine. Actually, if the machine is over-excited, only part of the excitation voltage is consumed in generating its own emf and the rest is available to provide leading excitation current into the system.

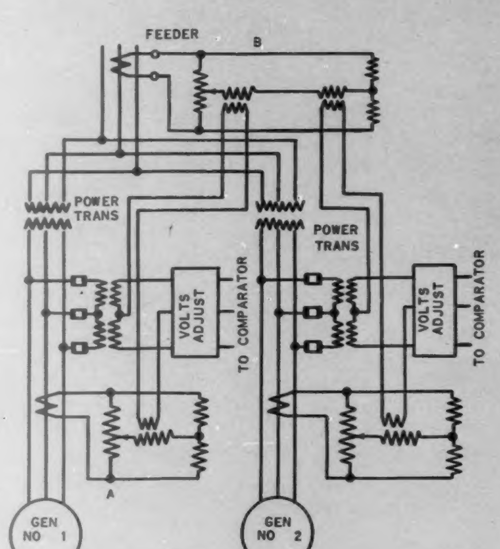
If the vector relations of Figure 3(C) for generator output are considered positive and the power angle α swings to the negative side as the machine becomes a motor, vector diagram of Figure 10(A) results. In this case the machine is taking power from the line, will sustain its own rotation, and can even deliver mechanical power from its shaft. The mechanical power delivered determines whether the machine is a synchronous motor or a synchronous condenser, the latter supplying no mechanical power. The power factor angle θ' is greater than 90 degrees. With counterclockwise phase rotation and with I leading — V, the machine will be taking leading current and will have comparatively high excitation and high internal voltage E. Figure 10(B) shows the condition of comparatively low internal voltage and reduced excitation which draws a lagging current and Figure 10(C) shows the conditions at unity power factor.

Therefore the power factor of a synchronous motor or synchronous condenser operating under constant voltage and frequency may be varied by changes in field excitation. Likewise when a synchronous motor or synchronous condenser is under the control of a voltage regulator, the voltage in that section of the power system can automatically be held constant by changing the input to the motor or condenser to leading or lagging reactive power to make up for the lagging or leading conditions on the power line.

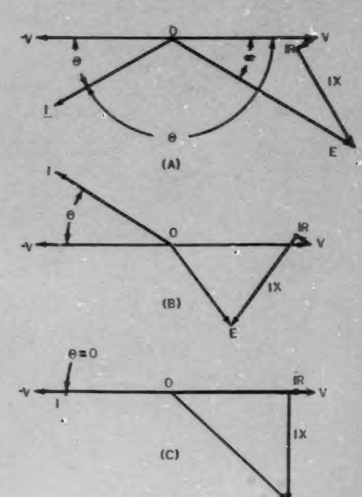
Thus the synchronous condenser is a useful device for controlling voltage and power factor on power systems. The control can be either manual, semi-automatic or automatic. In many instances stations are set up with completely automatic and unattended control where the conditions of the power line is measured by supervisory equipment and the condenser starts up and shuts down as required.



VOLTAGE DROPS in transformers and lines to the first point of distribution are offset by drop compensation. **(FIGURE 8)**



BALANCED COMPENSATION for two or more generators in parallel provides drop and reactive current compensation. **(FIG. 9)**



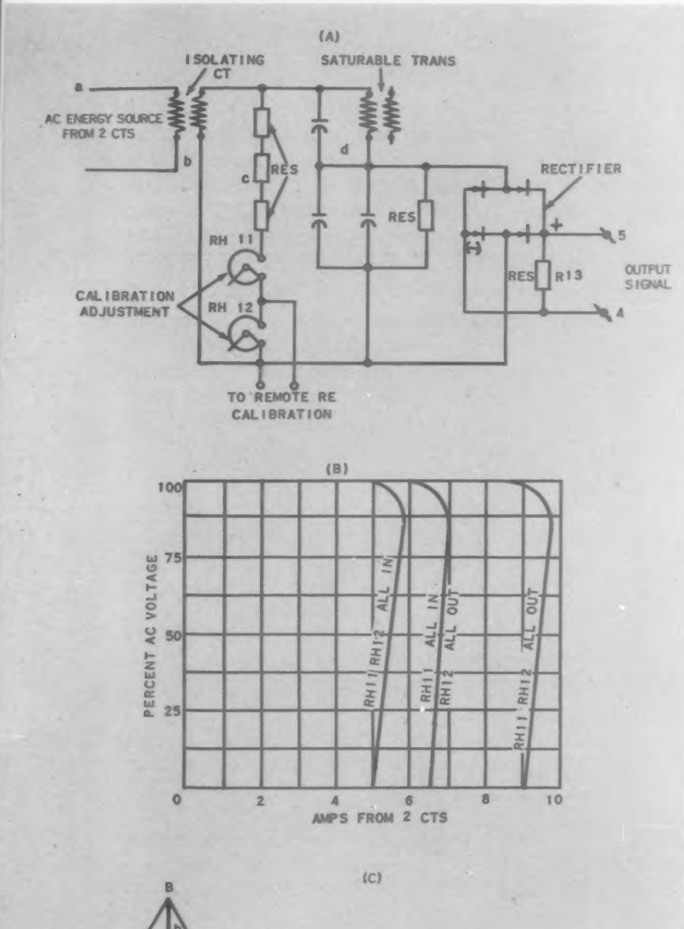
SYNCHRONOUS MOTORS not only drive mechanical loads but may offset inductive loads with leading current. **(FIGURE 10)**

When a synchronous condenser is accurately controlled by a voltage regulator, the voltage conditions may call for reactive power output beyond the thermal limits of the machine. This may happen under automatic control in an unattended station or under semi-automatic control when the attendant sets the voltage adjusting control too high.

Thermal protection is provided in the *Regulex* voltage regulator by the line current limiter which can be set for a definite ac line current above which voltage regulation is changed to regulation of the condenser output current.

Line current is limited

The line current limiter is a combination of static devices connected as shown in Figure 11(A). It is applied to the regulator circuit as shown at (2) in Figure 7. The current limiter input (a), Figure 11 is taken from two current transformers in lines A and C in the condenser output leads. The relation of the line currents with one current transformer reversed is shown by the vector diagram Figure 11(C). The resultant current D, Figure 11(C) is taken through the primary of the isolating transformer (b), Figure 11(A), and transferred to voltage across a series of resistors and two adjustable rheostats, RH11 and RH12, (c) in Figure 11(A) which set the line current at which the current limiter will operate. This voltage is then applied to a sensitive resonant circuit (d), Figure 11(A) consisting of resistors, reactors and capacitors; the capacitor drop is rectified and inserted, in the form of a dc voltage drop across resistor R13, in the comparator output circuit as shown at (3) Figure 7.



CURRENT LIMIT PROTECTION supersedes other control functions when the regulator calls for reactive current beyond the synchronous condenser or motor rating. **(FIGURE 11)**

The operation of the current limiter is typical of the functioning of the series resonant circuit. As the current in the condenser line is increased, the voltage across the resistor circuit c, Figure 11(A) and the voltage across the resonant circuit (d) also increases. Below the critical value of the resonant circuit, the entire voltage is absorbed across the saturable reactor and no voltage appears across the capacitor. When the voltage is increased to the critical point where the reactor saturates the impedance of the reactor drops and the voltage is suddenly transferred to the capacitive part of the circuit and produces an output signal at terminals 4 and 5.

The current limiter is connected in the comparator circuit with a polarity to oppose the aid signal of the comparator. Thus when the limiting line current of the current limiter is reached, the normal voltage regulation under the control of the comparator is superseded and the excitation current of the exciter is regulated to a value which produces only the maximum condenser current as set by the current limiter.

The overall operation of the regulator is described graphically in Figure 11(B). This plot is made between the comparator input volts and the condenser line current transformer output. Consider any current setting such as (1), Figure 11 representing the condenser current which will give five amperes from the current transformers. At any condenser current less than this value the effective comparator voltage remains at its normal value of 102 volts. If the condenser current rises to a value corresponding to 5.5 transformer secondary amperes, the effective comparator output is reduced as required to maintain the condenser current at this value.

Figure 11(B) also indicates that rheostat RH11 can be used over the usual design range of maximum current for the synchronous condenser. Most modern condensers are built with a temperature detector in contact with the machine windings. The temperature winding changes its resistance with temperature increase and actuates a bridge type temperature relay in the control equipment. A normally closed contact on the temperature relay shorts out RH12 under normal conditions, and permits the setting of RH11 to be adjusted in the higher range. However, if the machine windings reach a dangerous temperature, the opening of the temperature relay contacts will insert a predetermined amount of RH12 and recalibrate the current limiter setting to a lower range.. When no thermal devices are used RH12 is shorted out.

Rotating voltage regulators, properly applied to modern power systems, now provide an accurate control of the reactive current supplied to the system by each synchronous machine. This control governs circulating wattless current between generators, provides overcurrent protection for synchronous condensers, and compensates for line and transformer voltage drops.

OUTDOOR POWER PLANTS, becoming increasingly prominent in the warm climate areas, are both neat and practical because of the development of weather-protected equipment which combines reliability with eye appeal. This induced-draft and forced-draft fan section at a southern utility has only the sky for its roof. The forced-draft fan motor (rear) is rated 300 hp, 2300 volts, 1200 rpm while the induced-draft fan is driven by a 450-hp, 2300-volt, 695-rpm motor in the foreground. Installation shows another step made in the progressive development of improved outdoor equipment.

Allis-Chalmers Staff Photo

HYDROGEN COOLING 1951

by A. LEHRKIND
Motor-Generator Section
Allis-Chalmers Mfg. Co.

STANDARDIZED TURBO-GENERATORS with hydrogen cooling are approaching the packaged unit stage, as shown by this recent installation. All gauges, instruments and controls for operation of turbine and hydrogen systems are contained in the unit, minimizing installation problems.

Recent improvements and simplification of hydrogen cooling systems adapt them for higher operating pressures.

SINCE THE LAST "HERETICAL" statement in 1947,[1] "Vacuum treating of shaft seal oil is not necessary for maintaining hydrogen purity in turbo-generators," hydrogen-cooled generators have more than ever occupied the stage for all central stations and are rapidly invading the industrial field.

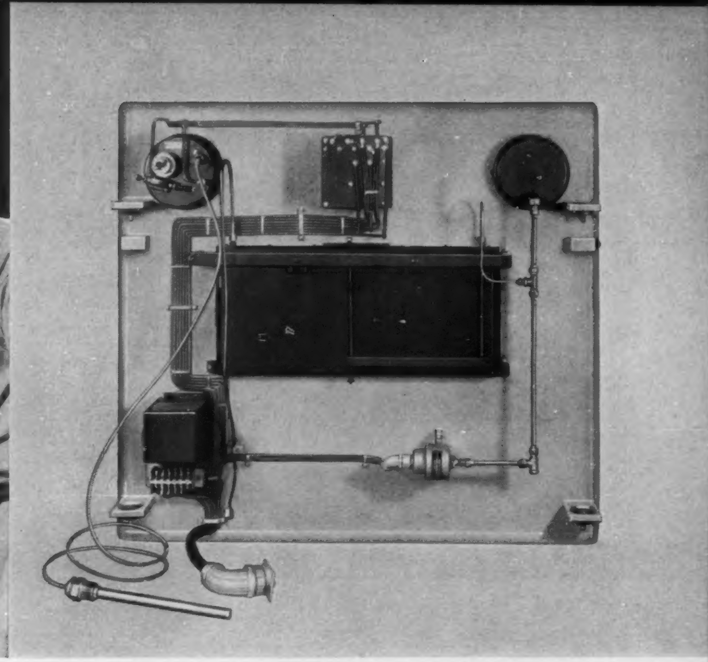
Most initial designs of hydrogen-cooled generators were made for a nominal hydrogen pressure of one-half pound above atmospheric pressure. Later the effect of improved thermal properties at increased gas densities encouraged the more general use of higher pressures to permit overloads. The AIEE-ASME Committee on Steam Turbine Generators then set up recommended standards for nominal ratings at one-half pound, overloads of 15 percent at 15 pounds. Since machines meeting these standards have been manufactured and tested, further increases in overload capacity have been obtained by raising the hydrogen pressure beyond the 15-pound standardized ratings to 25 or 30 pounds gauge pressure.

The shaft seal developed for turbo-generators has a babbitted surface held against a polished face on the shaft by the combined pressure of a set of coil springs to provide initial loading, gas pressure on the back of the seal ring, and oil pressure on the piston area formed between the two oil seals. This forms an effective seal to prevent loss of hydrogen under all conditions of loading without exposing the lubricating and cooling oil to the hydrogen atmosphere. The amount of oil required for cooling is practically independent of the oil and gas pressure, but the oil pressure must be kept above the gas pressure to prevent gas leakage. Therefore, to avoid pumping unnecessarily large quantities of oil to permit operating the generator at high gas pressures, the radial grooves, which act as nozzles to control the oil flow, have been reduced to maintain approximately the same flow at high pressures as was previously provided at lower pressure. Consequently, no change in the oil system to permit 30-pound gas pressure has been required except to provide 35 pounds oil pressure.

[1] *"Hydrogen Cooling Simplified,"* King, W. F., and Lehrkind, A., Allis-Chalmers *Electrical Review*, Third Quarter, 1947.

MODERN HYDROGEN SEALS are structurally simple but provide excellent hydrogen retention. "O"-ring gaskets are shown being inserted into their respective grooves in the babbitted seal ring before the upper half of the end cover is lowered into position. (FIGURE 1)

INSTRUMENTS FOR HYDROGEN supervision in a standardized generator are contained on small panel shown above. Hydrogen purity is read from chart which shows purity from gas and fan pressure indications. Inclined gauge expands the fan pressure scale for easy reading. **(FIG. 2a)**



BACK OF HYDROGEN INSTRUMENT panel shows its simplicity. Electrical connections are made through one multiple connector. The vibration mountings with pin type connection to brackets on generator permit quick removal in the event that laboratory checking is required. **(FIGURE 2b)**

Development of the shaft seal, described in detail in the previous article on hydrogen cooling, has continued with operating experience serving as a guide in developing further changes to reduce size and weight and to lengthen the periods of operation. The early type of seal for the oil chamber, described as a "cup-washer," which required a retaining ring bolted in place, has been replaced by a rubber ring of circular cross section simplifying machining and assembly (Figure 1).

The bearing surface on the generator shaft, against which the babbitted seal mates, was a hardened steel ring bolted to the shaft in order to provide a replaceable surface in case of excessive wear. Elimination of this ring was also directed by operating experience. The shaft surface itself is carefully finished to provide a more dependable, long-wearing, true-running thrust face for the seal.

System greatly simplified

Laboratory instrumentation for the first hydrogen-cooled generators led to commercial installations having very nearly the same equipment with a control cabinet containing motor controls, pressure and purity transmitters, control valves and alarm equipment. A separate remote panel was provided with pressure and purity recorders located adjacent to the turbine gauge board. As laboratory control was proved unnecessary, various parts of the equipment were omitted until the present arrangement evolved. Hydrogen control instruments are now located on a small panel on the generator. As shown in Figures 2a and 2b, this simplified panel arrangement has eliminated the long runs of gauge piping and complicated instrumentation of earlier design.

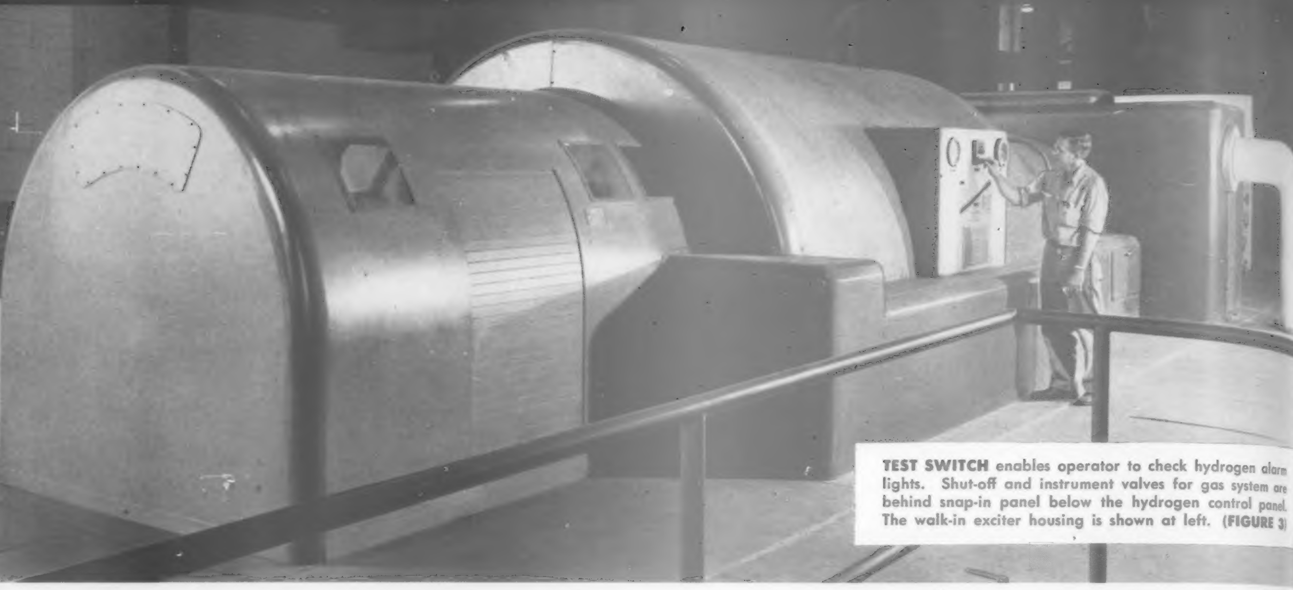
Gas temperature, pressure, and purity instruments and the alarm lights for indicating abnormal conditions of operation are mounted on this panel. Purity indication is based on fundamental measurements, avoiding any loss of accuracy during the life of the machine. A measurement of the pressure developed by the generator fan, which runs at constant speed, indicates the density of the gas mixture when compared with the reading obtained with air during the initial operation of the machine. The density determines the proportions of air and hydrogen in the mixture.

As a safety precaution, shut-off valves are provided in the hydrogen piping as close to the generator shell as possible so that if the piping should be damaged in any way during operation the gas in the machine can be sealed in to avoid loss of power production while repairs are being made. These shut-off valves were formerly located near the bottom of the generator shell where the pipes dropped downward to the gas manifolds. This location frequently proved inaccessible. To provide ready access, valves are now placed under the side covers of the generator above the turbine floor line behind a snap-in cover, as shown in Figure 3.

The location and arrangement of hydrogen and carbon dioxide cylinders and the associated valves and piping for scavenging, filling, and maintaining hydrogen in the generator required extensive layout in the older installations. Because of the many details involved, these initial installations were cumbersome and often a nuisance. Today, the hydrogen-cooling system is standardized so that space requirements can be determined immediately from available drawings. Units can be assembled on the site to suit the station's available space, as shown in Figure 4. The manifolds, Figure 5, can be located at any point in the plant or adjacent buildings. The system can be assembled in a straight line or around the walls of a room if desired. Two pipes connect to the generator shell and a third discharges the scavenged gas to atmosphere outside the plant.

The purpose of the gas manifolds is to provide a convenient means of filling the machine and automatically maintaining gas pressure at any desired value without constant attention.

For maximum benefit the location of the manifolds should be chosen with care. Generally, attention is required only once a day so that convenience to the operator is not the guiding factor. The handling of gas cylinders is the most important consideration in locating the manifolds. Trucks, therefore,



TEST SWITCH enables operator to check hydrogen alarm lights. Shut-off and instrument valves for gas system are behind snap-in panel below the hydrogen control panel. The walk-in exciter housing is shown at left. (FIGURE 3)

should be provided with easy access to cylinder stations for convenient loading and unloading.

Higher loads with smaller machines

Operating experience at elevated hydrogen pressures has proved satisfactory and in several plants has reduced the temperature and expansion effects associated with emergency operation above the nameplate rating. Initially, half-pound operation was made the nominal standard hydrogen pressure because it was the lowest practical point which would insure that any gas leakage would flow out of the generator casing or apparatus, avoiding a reduction of gas purity within the enclosure. The gradual improvement in manufacture helping to reduce the rate of gas leakage permitted increases in pressure to obtain the advantages of better heat transfer at greater gas densities. Tests confirmed calculations that approximately 15 percent overload could be carried at two atmospheres absolute pressure. The observed temperatures indicate that even greater loads could be carried, but heat transfer calculations show that the margin between indicated and assumed hot-spot temperatures should be increased to avoid overheating. Favorable reports on 15-pound operation have brought about specifications for nominal 15-pound ratings, permitting a machine of smaller size for a given load rating. With this development has come the next step in design — 30-pound gas pressure. An overload of 25 percent above the half-pound rating has been found feasible for this pressure.

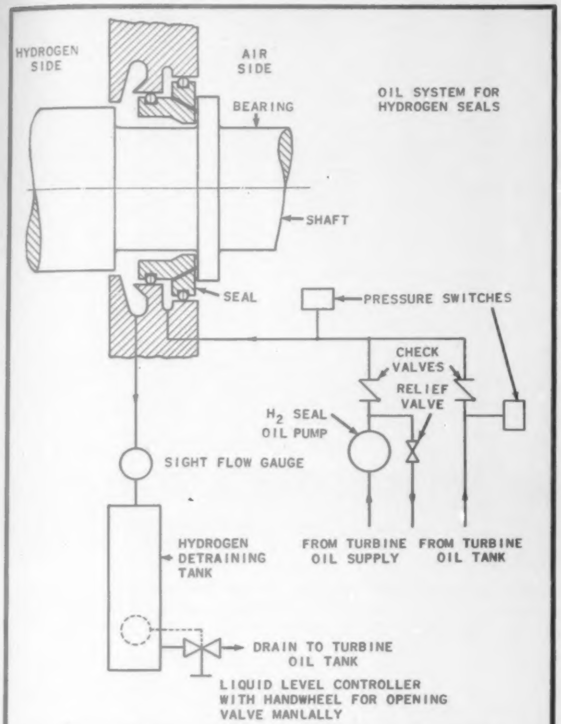
Realization of the full possibilities of 30-pound gas pressure requires the design of auxiliaries and all component parts of the system to be suitable for the maximum rating. In the case of machines already built the limitation of load will probably be found in cable heating or some similar part. Usually, some components must be modified if the normal temperature rises are to be maintained.

The shaft seal oil system required for 30 pounds gas pressure is no more complicated than before (Figure 6). Normally, the main turbine oil pumps are used for the supply with a pressure regulating valve admitting the required oil directly to the shaft seals. The seal oil pressure is maintained at a value two to five pounds above the maximum gas pressure to be used, and the seal oil passages are designed to provide proper lubrication and cooling of the seal at this pressure. Under these conditions the oil flow into the hydrogen atmosphere will vary slightly at different gas pressures but is so small in any case as to be unimportant. This oil collects in the detraining tank, simply a settling chamber, until released by a float valve to return to the main oil tank, as shown in Figure 7. The float valve can be replaced by a long "U" tube to eliminate the possibility of mechanical failure, if the installation of a few sections of well casing is preferred. The hydrogen seal auxiliary oil pump starts automatically to maintain the normal oil pressure and flow whenever the main oil pumps are shut down. The selector switch (hand, off, automatic) has been removed from the system to prevent accidental shut-off of the auxiliary oil pump.

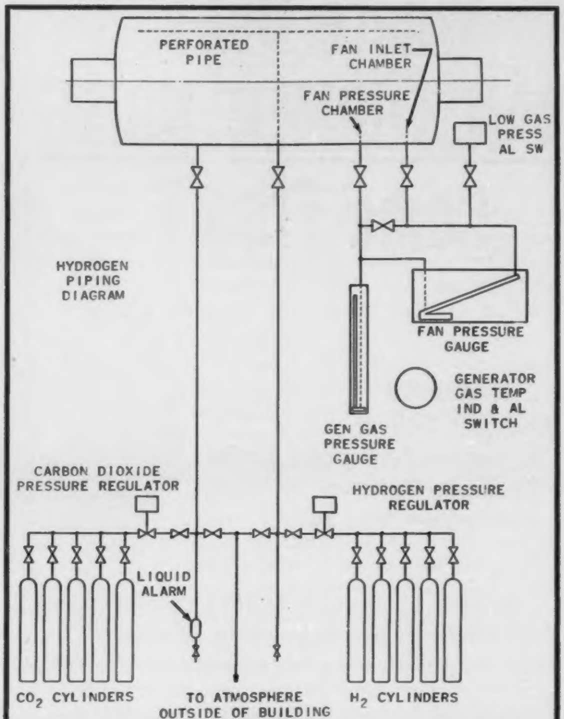
New seal cuts gas leakage

Compared with the cup washers previously used, tests of the thrust type hydrogen seal without oil pressure show improved sealing ability using O-ring oil chamber seals. This permits retaining hydrogen in the machine for short periods at standstill without oil pressure. At half-pound pressure the leakage is negligible; at one pound, one cylinder of hydrogen will maintain the pressure for a half hour or longer. When operating at 15 pounds or higher, operation without oil pressure is less certain, but the loss of gas will be much slower than with any other type of seal. The worst case tested showed that at 15 pounds one cylinder of gas would maintain the pressure for 10 minutes. Any leakage of gas into the oil piping will,

CARBON DIOXIDE SECTION of a standard manifold is shown in foreground, with hydrogen cylinders at far end. Control valves, regulators and gauges are conveniently located in the center. (FIG. 4)



GAS PIPING can be shut off at the generator if any emergency makes it necessary. The gas manifolds can be located remotely or close to the generator, as desired. **(FIGURE 5)**



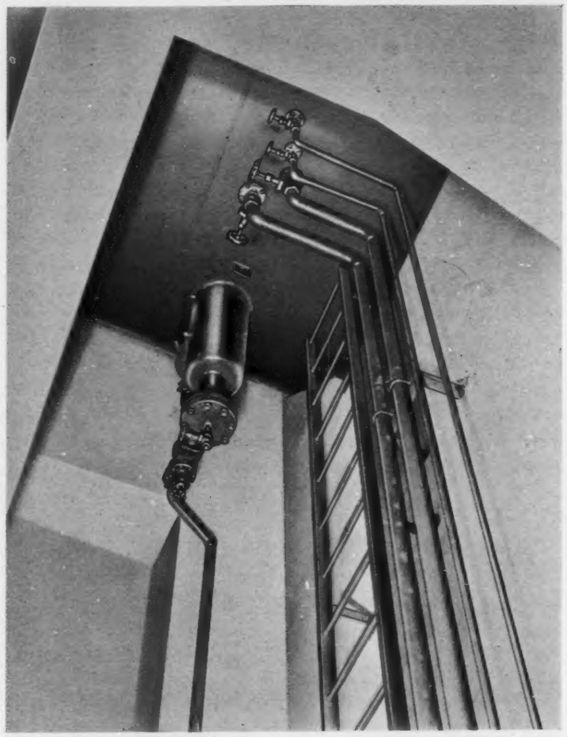
HYDROGEN SEAL, cross section in diagram, is normally supplied from the turbine oil pumps. The independent seal oil pump starts automatically whenever the main supply is stopped. **(FIG. 6)**

of course, travel to the main oil tank, and the venting of the space above the tank is the most important item in avoiding the accumulation of gas at that point.

A hazard of accumulating gas upon loss of seal oil pressure has led some users to specify a dc emergency pump in addition to the ac auxiliary pump. While this offers some additional protection in case of a longer outage, it does not guarantee that failure will not occur. An alternate method of protection, which has not been used but could easily be supplied for high pressure machines, would be a solenoid valve held closed by energy from the station auxiliary bus. This valve would open to the atmosphere pipe releasing the high machine gas pressure in case of power failure and thus preventing continued discharge of gas into the oil system. Reports of trouble caused by gas leakage in connection with hydrogen-cooled generators are so rare that the thought of additional apparatus seems foreign to the subject.

A concurrent development which promises to greatly enhance the benefits of elevated pressures in hydrogen cooling has proved its merit in commercial operation of the first "supercharged" generator.[2] This generator employs a compressor mounted on the shaft to force hydrogen at high velocities through ducts in contact with the conductors. The importance of this most recent step in design has had little time to become known to the country's engineers outside the circle of those directly concerned with the present installation, but there is little doubt that the initial predictions will be exceeded.

The operating record of all hydrogen-cooled generators has in every way confirmed early predictions of the great advancement possible with hydrogen cooling. This is endorsed by the ever increasing number of new installations.



WELDING DETRAINING TANK to bottom of generator shell eliminates support problem and permits prefabrication of seal oil system without interference with other power plant equipment. The four pipes show normal arrangement prior to the advent of valves above the turbine floor. **(FIG. 7)**

[2] *"Supercharged Cooling of Generators,"* Beckwith, S., Allis-Chalmers *Electrical Review*, Third Quarter, 1951.

Where Does TRANSFORMER NOISE Come From?

by **T. F. MADDEN**
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Pittsburgh Works
Allis-Chalmers Mfg. Co.

AUDIBLE SOUND LEVEL readings on a 600-kva, dry type core and coil assembly are being taken by author prior to tanking. Tank outline drawn on floor helps to locate test points. Results of audible sound tests before and after tanking are compared to evaluate tank attenuation factors.

Modern noise level testing facilities and procedures are helping to eliminate factors contributing to transformer noise.

INTEREST IN TRANSFORMER NOISE has increased considerably in the past decade as is evidenced by the numerous questions on the subject presently confronting transformer manufacturers and users. Modern power distribution practices necessitate the installation of units of considerable size in locations where transformer noise may readily be a source of annoyance. Many users have been confronted with numerous complaints resulting from such installations. With the trend toward the installation of substations near the load centers and within residential districts, quiet transformer operation is becoming increasingly important.

Neglecting auxiliary equipment such as fans and coolers, the sources of transformer noise may all be identified with the core and coil assembly. The main source of noise is magnetostrictive vibrations generated in the core as a result of minute dimensional changes in the core material which accompany magnetization. When silicon sheet steel is magnetized an elongation takes place in the direction of magnetization as shown in Figure 1. When a core constructed of such material is magnetized with an alternating magnetomotive force, the elongations are translated into periodic mechanical vibrations. The complex mechanical vibrations of the core may be represented by a Fourier series expansion of the form

$$\Delta(t) = \sum_{n=1}^{N} A_n \cos\,(2n\omega t + \phi_n) \qquad (1)$$

where $\Delta(t)$ is the vibrational amplitude of the core in micro-inches
n is an integer 1, 2, 3 . . .
ω is 2π times line frequency
A_n is the nth harmonic magnetostriction amplitude in micro-inches
t is the time in seconds
ϕ_n is a phase angle resulting from the combination of sine and cosine terms.

These core vibrations generate audible noise which has a fundamental frequency of twice the supply frequency, or 120 cycles per second for a 60-cycle installation. As a result of the parabolic nature of the magnetostriction characteristic shown in Figure 2, integral multiples of the fundamental will also occur in the noise spectrum. In the above expansion it is usually sufficient to make N a maximum of six because the magnetostriction amplitudes are generally negligible beyond the sixth harmonic of the fundamental megnetostriction frequency.

Secondary noise can be controlled

Other possible sources of noise include those attributed to faulty core construction, namely defective gaps and interlaminar vibrations. Another source of noise is the vibration of the coils resulting from the load currents circulating in the windings. These three sources are of secondary importance as noise generators and in a properly constructed transformer will not contribute materially to the overall noise level as determined by magnetostrictive vibrations in the core.

Though not actually sources of noise, resonance conditions in the mechanical structures of the core and coil assembly and the finished transformer must be given due consideration in efforts to reduce transformer noise. Coincidence of natural frequencies in the mechanical structure and the magnetostrictive frequencies will enhance the noise frequency component at which resonance occurs and may result in a considerable increase in the noise generated. On the other hand, resonant free structures, particularly the transformer tank, will attenuate the noise generated by the core and coil assembly by virtue of its mass and rigidity. Of the core and coil noises, magnetostrictive noise is paramount and must be reduced before other noises can be controlled.

Magnetostriction is inherent

From the standpoint of noise generation, it would be desirable to employ a magnetic material having zero magnetostriction in the construction of a transformer core. However, mechanical and economical considerations as well as magnetic requirements which dictate the choice of the core material to

be used are not compatible with the characteristics of presently available materials of low magnetostriction.

It is known that a composition of electrical sheet steel containing approximately 6¼ percent silicon has essentially no magnetostriction; however, the high silicon content renders the steel far too brittle to withstand the shearing and handling operations involved in the fabrication of a transformer core. A further disadvantage is that increases in silicon content reduce the saturation induction value. Variations in magnetostriction presently obtainable by variations in silicon content or by the addition of other alloying constituents do not constitute a sufficient reduction in noise level to warrant the use of materials of otherwise inferior magnetic and mechanical properties.

The choice of the value of flux density used in designing a core will have considerable effect on the noise generated as a result of the interrelation between flux density and magnetostriction. Figure 2 indicates the variations of peak magnetostriction with the maximum value of flux density. Along with the increase in the amplitude of the magnetostrictive vibrations there also occurs an increase in the predominance of the higher harmonics generated. The effect upon the noise generated is therefore twofold in that the sound intensity is greater and a considerable portion of the noise generated occurs at frequencies for which the response of the ear is greater.

Figure 3 indicates the variation of the noise level with induction for various transformer ratings. A ten percent change in induction will alter the noise level by three to four decibels.

Noise controlled by mechanical design

The mechanical design of the core, from a noise standpoint, although generally overlooked, may have considerable bearing on the final noise level of a transformer. Should a critical geometry of core punchings be used, resultant mechanical resonances may enhance one or more of the magnetostriction frequency components resulting in a considerable increase in the noise level. The resonant frequencies of a simple core structure can be expressed as follows:

$$f = K \frac{b}{l^2} \qquad (2)$$

where K is a function of the material constants and the core dimensions, b is the punching width, and l is the length of the leg steel.

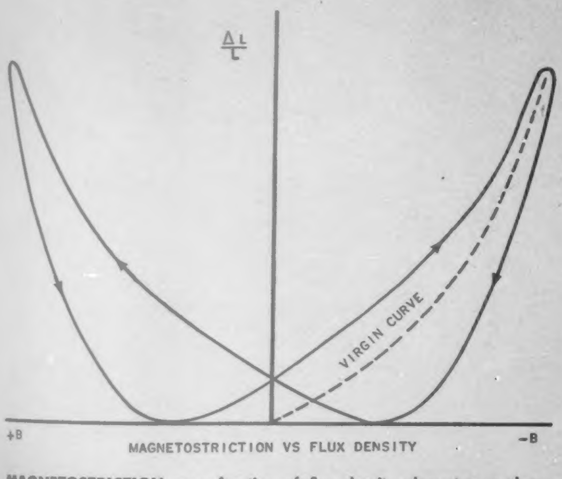
Through the use of such information in designing the core, it is possible to avoid mechanical resonances within the core, thereby minimizing the noise generated for a given flux density.

The proper interleaving of laminations and construction of joints in a butt and lap core is important in minimizing the noise generated by a given core. Lamination "slap" produced by the former generates a buzzing sound distinguishable from the noise produced by magnetostriction. This source of noise can be avoided by proper construction and may be easily suppressed by firmly clamping the core.

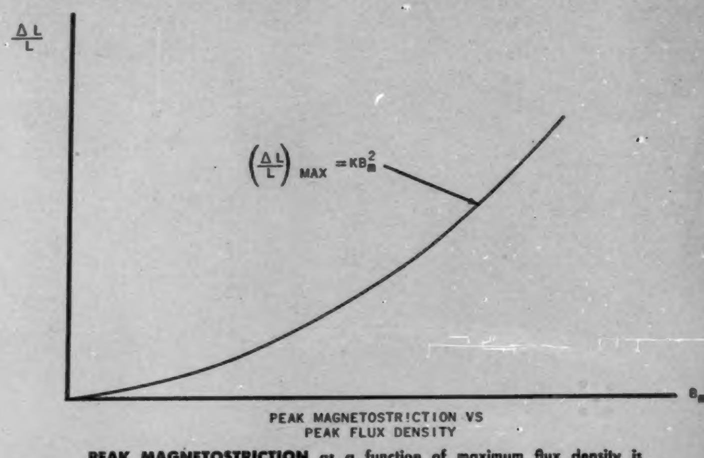
Improper joint construction will give rise to a high pitched noise also differing from the characteristic transformer hum. Proper clamping at the core joints will eliminate the noise attributable to poor joint construction. The more important consequences of poor joint construction are the large increases in exciting current and core loss resulting from poorly fitted laminations.

The damping effect of the insulating liquid will generally reduce the noise resulting from these two sources to some extent. In dry type transformers, core impregnation has been found to be a satisfactory means of eliminating this type of noise. The process binds the core punchings into a solid mass, thereby eliminating the noise attributable to these two sources. However, there are many disadvantages in this procedure which prohibit its use on a production basis. Obviously, neither the impregnation process nor the damping effect of the insulating liquid will correct the effect of the air gaps upon the magnetization characteristics of the core. Figures 4 and 5 show the variation of the magnetization characteristics for various gap conditions. Measured gaps were built into a butt and lap core in the manner shown in Figure 6 to determine these results.

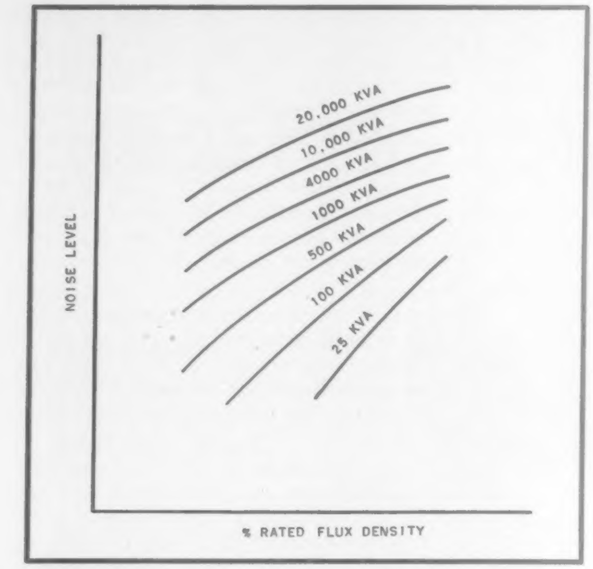
The core punchings of a core type transformer are clamped by means of side frames at the top and bottom of the core. The pressure applied by these frames is of the order of 20 to 25 pounds per square inch of side frame bearing surface which is sufficient to suppress the noise generated by the two sources mentioned above. It has been found that increases in clamping pressure beyond the values normally used will not reduce the noise level of the transformer. Only at low values of clamping pressure, where core construction faults can give rise to noise, will increases in clamping pressure have a notable effect.



MAGNETOSTRICTION as a function of flux density elongates as shown when hot-rolled silicon sheet steel in the core is magnetized. **(FIG. 1)**



PEAK MAGNETOSTRICTION as a function of maximum flux density is shown above. Core contained hot-rolled silicon sheet steel. **(FIGURE 2)**



FLUX DENSITY used in transformer core and coil design affects the intensity of core noise. A ten percent variation in induction will alter the noise level by three to four decibels. (FIGURE 3)

SOUND AND HARMONIC analyses of each distribution transformer design are conducted according to NEMA and ASA Standards. One step of test is shown being made on a 10-kva distribution transformer.

Load current noise is small

Load currents flowing in the transformer windings generate audible noise at double the supply frequency. Tests have shown that the level of the noise thus generated by the coil vibrations does not materially contribute to the overall noise level of the transformer as determined by the magnetostriction vibrations. Figure 7 shows that the noise produced by these current forces follows the square law as long as the condition of linear constraint is imposed on the motions of the coils. This may be expressed as follows:

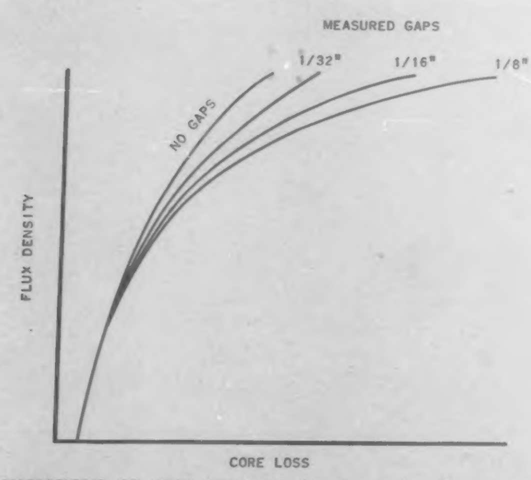
$$F \propto i^2 \qquad (3)$$

where F is the resultant force and i is the value of current flowing in the winding. The restraint results from the insulation and spacing blocks used in the construction of the winding assembly. The resilience of these materials is reasonably linear for small deflections, but at increased loads the increase in the deflections of spacers and insulation diminishes rapidly. Therefore, for low current values the coil deflections are small and hence experience a linear restraint. However, as the current increases, the condition of linear restraint disappears and the coil motion is limited. As is shown in Figure 7, further increases in load current after this condition is reached will not appreciably increase the noise thus generated. The results recorded in Figure 7 are similar to those shown by Swaffield[1] in his investigation of a model transformer.

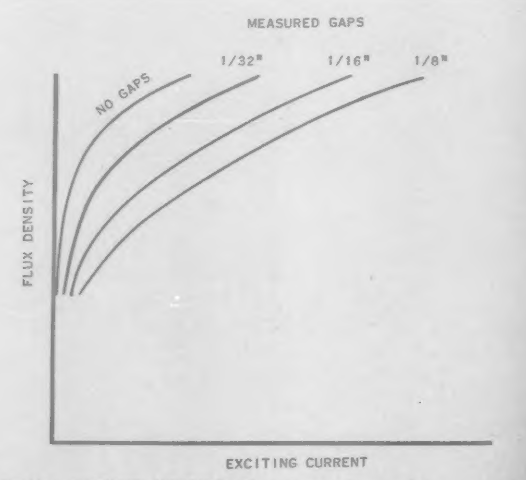
Analytical approach is complex

In oil immersed transformers the oil surrounding the core and coil assembly attenuates the vibrations generated in the core by virtue of its mass and viscosity. It also acts as an incompressible liquid and hence serves to transmit core vibrations to the tank wall from which sound waves are radiated. In dry type transformers the core vibrations transmit the air-

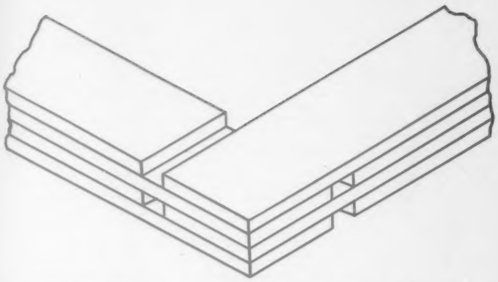
[1] *"The Causes and Characteristics of Transformer Noise,"* Swaffield, J., Institute of Electrical Engineers Journal, p. 222, Vol. 89, 1942.



VARIATIONS OF CORE LOSS with flux density for different gap conditions are plotted above. Curves indicate the importance of minimizing air gaps in the construction of core joints. (FIGURE 4)



EXCITING CURRENT VARIATIONS indicate that exciting current increases with flux density and increased air gaps. Insulation liquid or impregnation will not correct the effects of air gaps. (FIGURE 5)



CORE LAMINATIONS were constructed butt and lap, as shown above, to obtain variations in air gaps needed to investigate their effect on core loss and exciting current under varying flux density conditions. **(FIG. 6)**

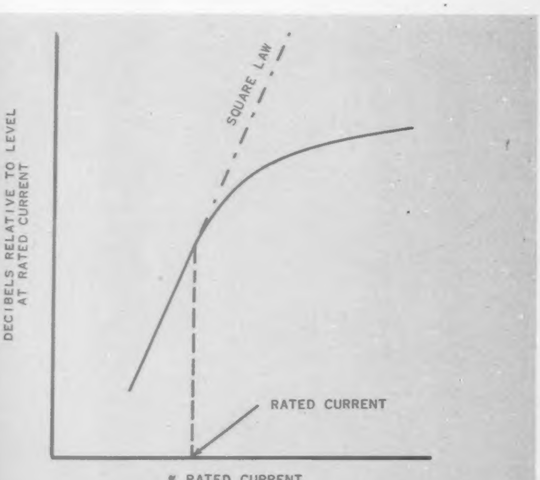
borne sounds directly from the surface of the core and coil assembly.

The attenuating effect of the oil as well as its ability to transmit vibrations are dependent upon the density of the oil, the size of the core and coil assembly, the size and geometry of the tank, and the volume of oil surrounding the core of the transformer. The attenuating effect may vary from 3 to 10 decibels depending upon the variables mentioned. The effect is influenced by the flux density used in the core and is found to diminish as the density increases.

The electrical clearances required internally, as well as the size and shape of the core and coil assembly, determine the geometry of the tank to be used for a particular design. From a mechanical standpoint the tank must be capable of withstanding the weight of tons of insulating liquid as well as being able to support the weight of the entire unit during transit and lifting. In view of the complex nature of the geometry of a transformer tank and its related structure, it is not feasible to attack the problem of natural frequencies in an analytical manner. The elimination of resonances and excessive vibrations in transformer tanks and their external appendages is primarily an experimental problem. The use of the harmonic index will greatly assist in determining the proper solution of this problem.[2]

Generally speaking, it is unlikely that the tank will resonate as a whole. Although small sections of the tank wall or attached components may vibrate excessively, there are so many vibrational modes in the mechanical structure that any one mode which may be excited will be considerably damped by non-resonant adjacent sections. Phase differences between the vibrations set up in adjacent sections will also damp the vibrational amplitudes in the tank wall.

[2] *"Harmonic Index — A Tool for Transformer Audio Noise Investigation,"* Mutschler, W. H., Jr., and Madden, T. F., AIEE Transactions pp. 115-118, Vol. 69-I, 1950.



NOISE LEVEL VARIATIONS shown above result from load currents in transformer windings. Above rated current, transformer noise no longer follows the square law because coil motion is limited. **(FIGURE 7)**

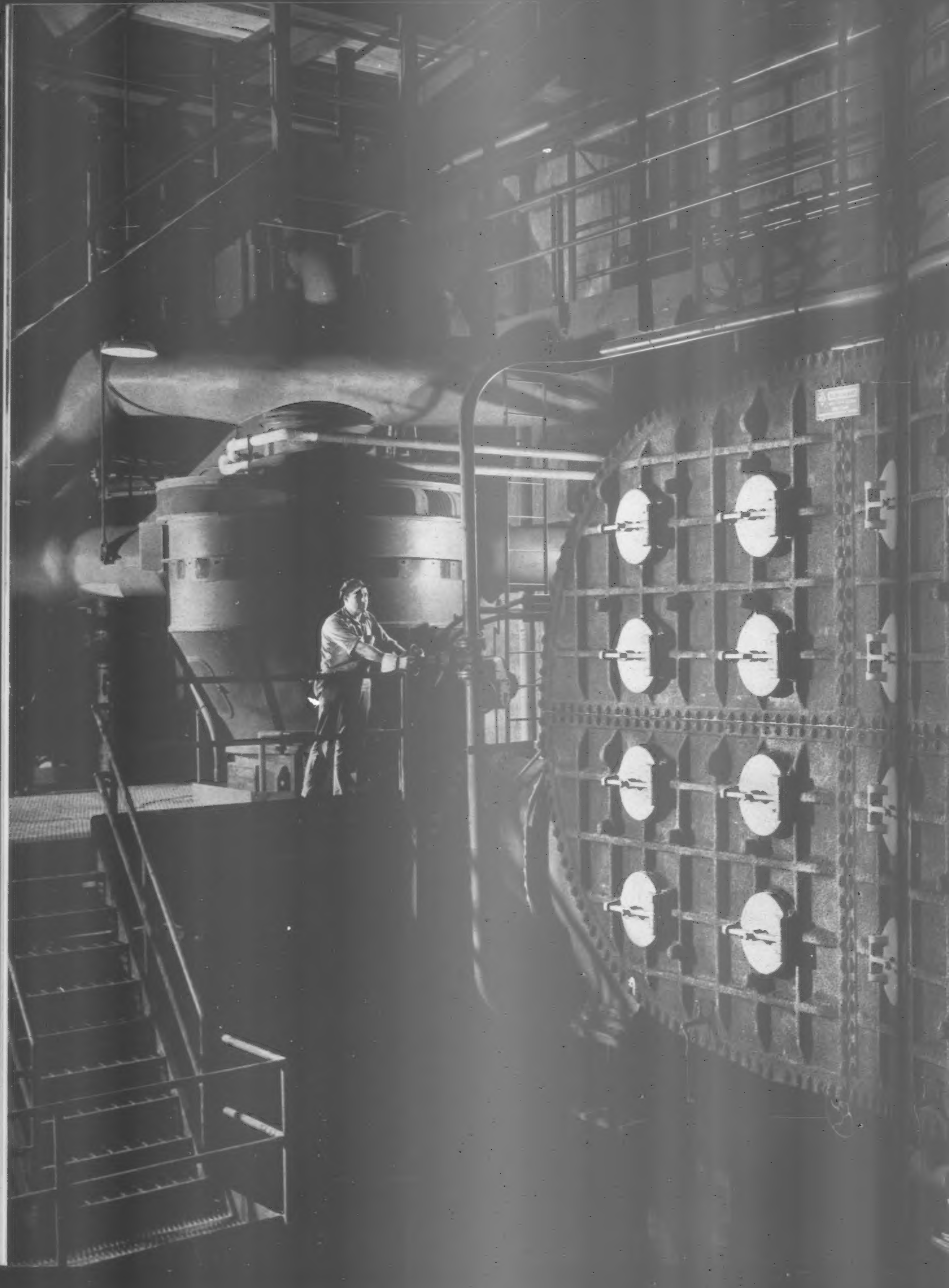
THIS 100,000-SQ. FT. single-pass surface condenser installed recently in a large midwestern generating station is supplied with a total of 150,000 gpm of cooling water circulated through 14,500 30-ft. long tubes by two vertical mixed-flow circulating water pumps, each driven by a 700-hp induction motor. Divided water boxes permit operation of one-half the condenser at any time. Flow can be reversed in either half for flushing.

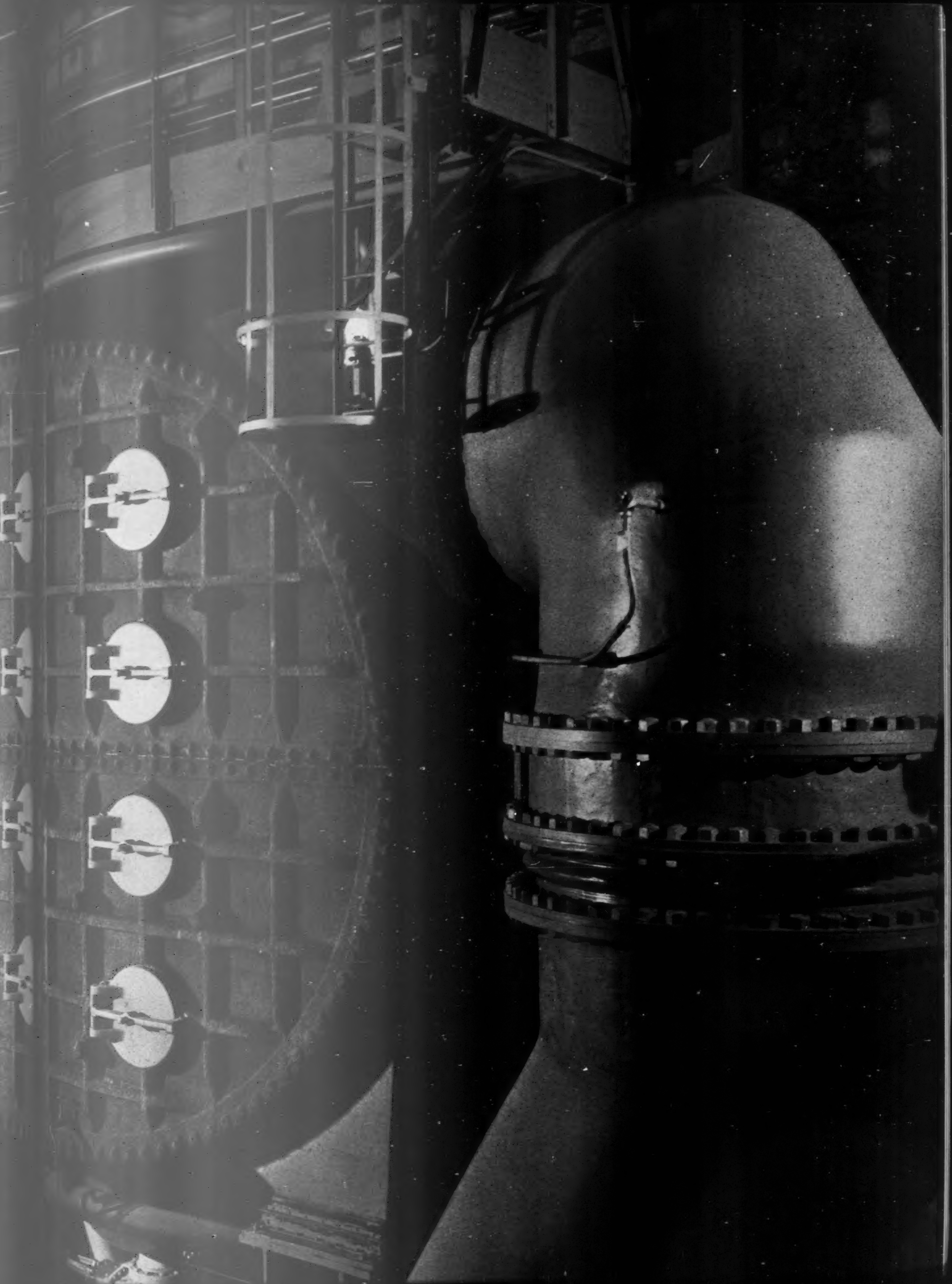
As may be expected, the mass and rigidity of the tank will serve to attenuate the noise to some extent. Tests have shown, however, that of the total attenuation due to the tank and oil combined, less than half is attributable to the tank wall in core type designs. Stiffening the tank walls will not necessarily increase the attenuation but may give rise to local resonances and will in effect reduce the overall attenuation.

Magnetostriction is controlling factor

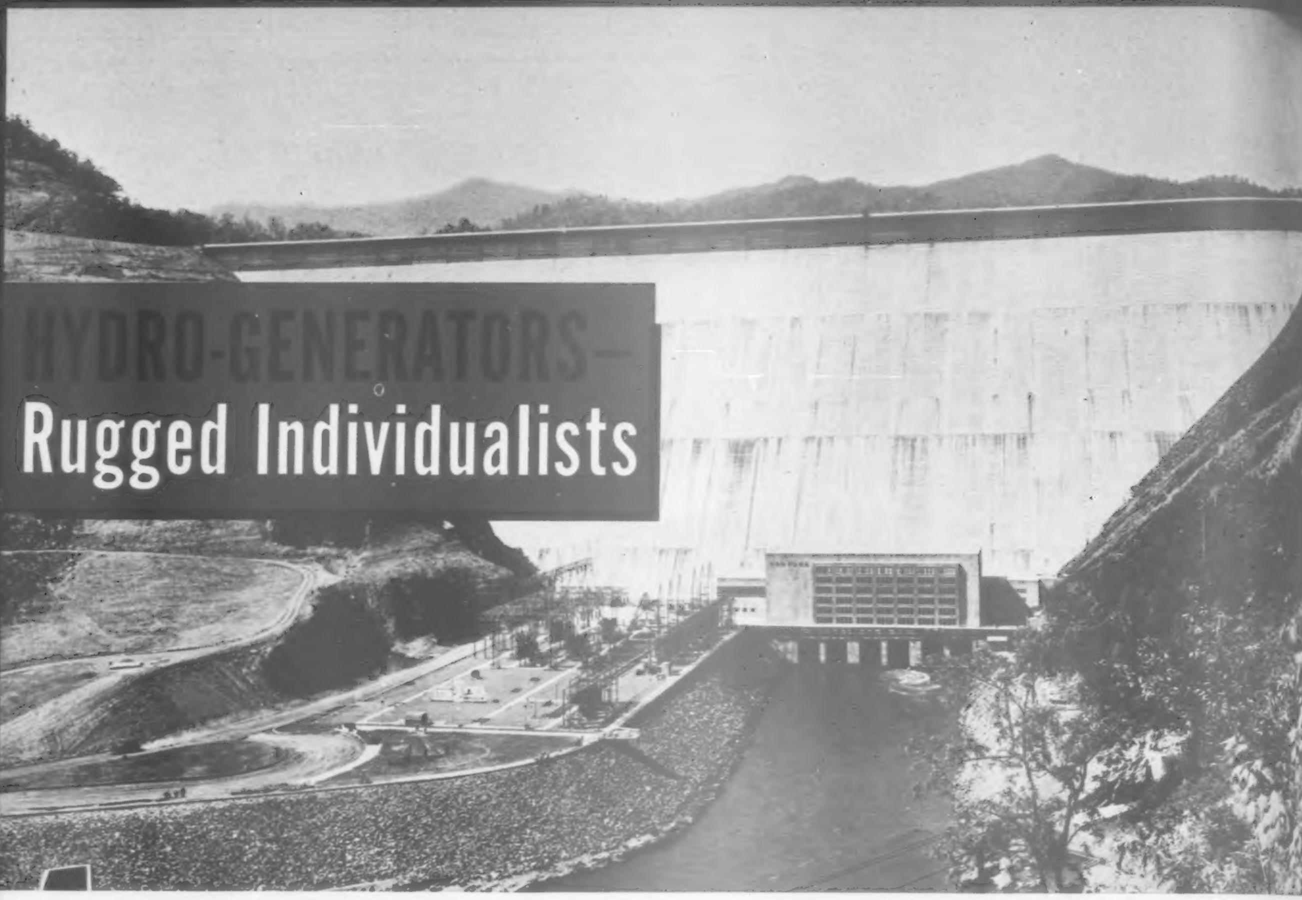
It is evident that the controlling factor in the generation of transformer noise is the magnetostriction characteristics of the core material. The development of an improved low magnetostriction electrical sheet steel which is economical and meets both mechanical and magnetic requirements would undoubtedly be a solution to many of the transformer designers' noise problems. For the present the designers' approach to the major noise problem is that of minimizing the noise generated by the magnetostriction of existing materials. This is done by avoiding mechanical resonances in the core and the tank structure and by reducing the flux density used in design. Experience gained through extensive noise level investigations provides the desirable guidance for future designs. Economy obviously sets a practical limit to the minimum flux density which can be used in achieving units of low noise level and of reasonable weights and dimensions.

MODERN TEST LABORATORY is equipped for sound level measurements as well as heat runs, and is used for both research and production testing. Shown below is a 1000-kva power transformer being prepared for sound level testing.





HYDRO-GENERATORS— Rugged Individualists



HYDRO-ELECTRIC PLANTS require a greater initial investment but cost considerably less than steam stations to operate and maintain. This plant has two 91,500-hp, 150-rpm, 330 to 433-ft head hydraulic turbines.

by H. H. ROTH
Motor-Generator Section
Allis-Chalmers Mfg. Co.

No two hydro-electric installations are alike. Generators for each plant must be individually designed to meet conditions.

STANDARDIZED electric generators have been mutually accepted by both manufacturers and users as the only means of satisfying rising power demands effectively and economically. Today's generators and other electrical equipment are built in standard ratings which are suitable for a wide variety of applications without modifications. One of the most significant developments along this line is the availability of steam turbo-generators in standard ratings ranging up to 100,000 kw.

A major exception to this trend are hydraulic turbine driven generators which cannot be standardized because of several restricting factors. The required characteristics of this type of generator are determined by the hydraulic turbine. Characteristics of the turbine are determined, in turn, by the hydraulic conditions of each installation. The available flow of water, net hydraulic head, length and size of penstock, speed regulation required, and the use or absence of a pressure regulator all affect the operating characteristics of the hydraulic turbine and its governor, which in turn determine the mechanical characteristics of the generator for each project. Since the flow of water or the height of dams cannot be standardized, it is frequently necessary to use non-standard ratings for hydro-electric units. Consequently, generators must be made for any rating that may be developed by the hydraulic turbine.

Speed is another vital consideration that sets steam turbo-generators and hydraulic turbine driven generators apart. For 60-cycle service, modern steam turbo-generators operate at speeds of either 3600 rpm or possibly 1800 rpm. Hydraulic turbines, however, are essentially low speed machines, with speed variations ranging from 50 rpm to 1200 rpm, depending on the hydraulic head available, and the type and size of turbine used. Therefore, generators for hydraulic turbine service must be built for a great variety of speeds.

A cross-section through a typical large hydro-electric generating unit is shown in Figure 1, where a dam is used to provide the hydraulic head and to store water. Water is conducted from behind the dam into the turbine through penstocks. It enters the turbine through the turbine scroll case, flows through the runner, and discharges through the draft tube into the tail race. A butterfly valve is provided sometimes to shut off water flow through the penstock, although other means may be used.

Hydraulic thrust load affects design

On vertical-shaft propeller and reaction turbines the generator thrust bearing must support not only the weight of the rotating parts of the generator and turbine, but must also carry the additional loading developed by the downward pressure of the water upon the turbine runner. Known as the hydraulic thrust of the turbine, it is a function of water pressure at the runner inlet multiplied by the projected area of the runner. Because of the very large projected area of a propeller type runner, the hydraulic thrust becomes large as compared to the thrust of a reaction type turbine for the same horsepower and head. To accommodate this increased loading, it is necessary to increase not only the size of the thrust bearing, but also the size of the generator thrust bearing housing, and possibly the size of the generator shaft. Thus the loading imposed upon the generator thrust bearing by the hydraulic turbine is an essential consideration in the design of a vertical generator. Figure 2 shows the approximate external thrust loads that are considered normal for vertical, 60-cycle generators. Any additional load will increase generator design requirements with corresponding increases in initial cost.

This hydraulic thrust is also developed by propeller and reaction turbines when a horizontal shaft setting is used. In such cases, however, the thrust bearing load consists only of the hydraulic thrust since the weight of the turbine and generator rotating parts is not imposed on the thrust bearing.

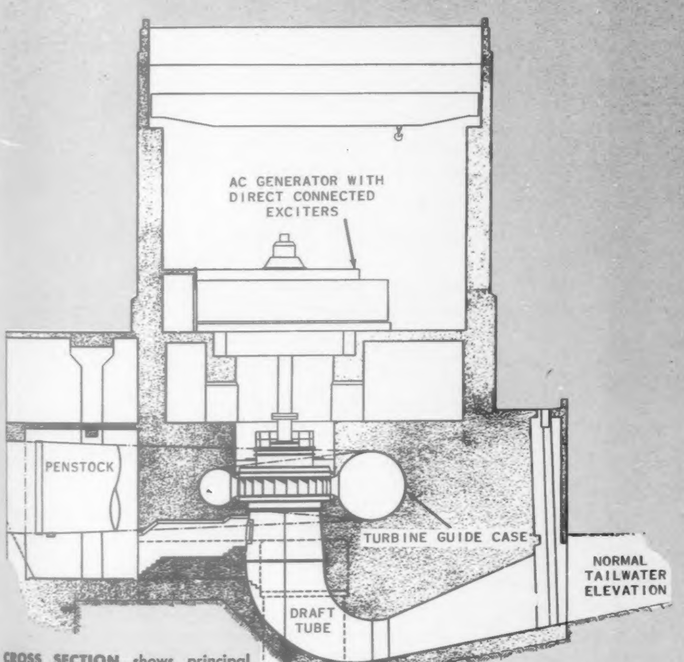
When the external thrust load imposed upon the generator by the turbine becomes greater than normal, the generator efficiency may be affected, since this additional load results in increased losses in the thrust bearing.

Overspeed complicates speed control

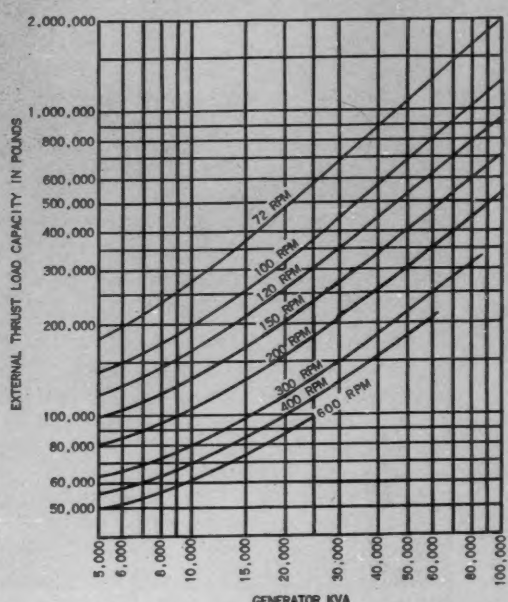
Any generator driven by a hydraulic prime mover must be built to withstand the full runaway speed of the turbine. Runaway speed may be defined as the maximum speed that the turbine will attain with maximum flow of water through it, and no load on the generator. Under such conditions the turbine speed will increase to as much as 175 percent to 260 percent of rated speed. Since the centrifugal forces set up in the generator rotor vary with the square of the speed in rpm, it becomes evident that the rotor construction is vitally affected by the runaway speed of the turbine.

In the case of sudden loss of load on a steam turbo-generator, the governor action is fast enough to limit the speed rise to a relatively small value. In addition, steam turbines are provided with an overspeed trip which instantly shuts off the steam supply in the event the turbine tends to overspeed above a certain rpm. It is not possible, however, to apply such governing to hydraulic turbines. Any attempt to shut off the flow of water to a hydraulic turbine suddenly will result in destructive pressure rise in the penstock. This is due to the fact that water is non-compressible as compared to steam. This pressure rise is also known as water hammer, and the amount of pressure rise is affected by the length of the penstock, velocity of water flow through the penstock, and the rate of deceleration of the water.

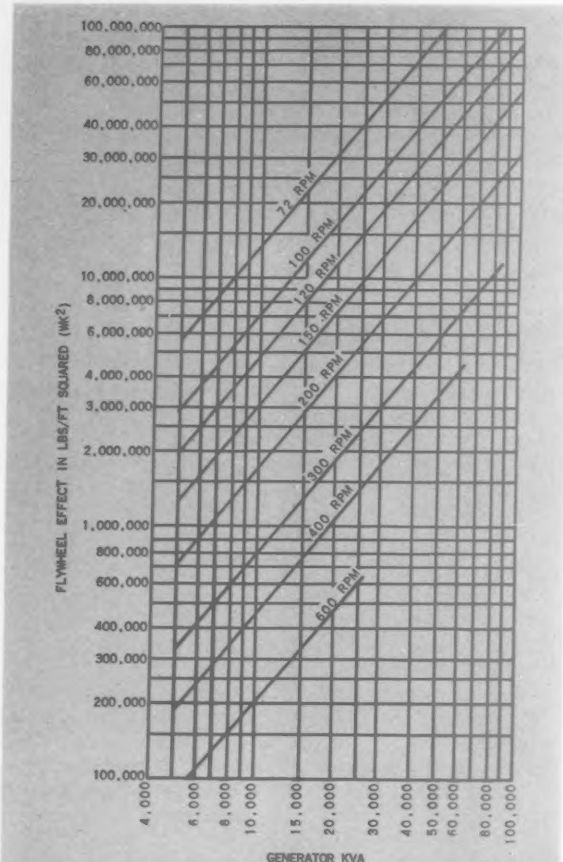
Thus it becomes necessary to set the governor of a hydraulic turbine so that the flow of water will be shut off at a rate sufficiently slow to prevent damage to the hydraulic portion of the power plant. Should there be a sudden loss of load at a time when the unit is carrying full load, the turbine speed will increase rapidly and may attain full runaway speed before the governor can be permitted to limit the speed. Full overspeed might also be attained because of a failure of some portion of the governor equipment followed by a loss of load. To protect life and equipment, rotors are normally



CROSS SECTION shows principal components of a conventional hydro-electric power plant. **(FIGURE 1)**



AVERAGE EXTERNAL THRUST load capacities of vertical generators are shown by curves. Thrust loads higher than those shown require heavier thrust construction. **(FIGURE 2)**



AVERAGE FLYWHEEL EFFECT of hydro-generators shown on chart are adequate for most installations. Greater than normal flywheel effect (WK^2) increases generator cost. **(FIGURE 3)**

built so that the maximum stresses at full overspeed do not exceed two-thirds of the yield point of the material used. The normal design of generators for hydraulic service provides for runaway speeds of 200 percent of rated speed for machines below 360 rpm, 50,000 kva and smaller. For machines 360 rpm and above, and for all machines above 50,000 kva, the normal design provides for 185 percent runaway speed. Higher than normal runaway speed increases the cost of the generator.

Flywheel effect

A third variable which may require evaluation is the amount of WK^2 (flywheel effect) that must be incorporated in the generator rotor. Although this was of considerable importance in earlier installations where a hydro-electric plant might operate as an isolated system, it is of less importance today. Hydro-electric plants or generating units now are usually operated as part of a large system and higher than normal WK^2 is usually of no particular value for fluctuating load conditions. In some cases, system stability studies may indicate the desirability of additional WK^2 although the use of high speed switching now available is usually preferable to higher WK^2 and slower switching. The chief benefit of higher than normal WK^2 on modern units is in limiting the overspeed upon a sudden loss of load. Since generators are built to withstand the full turbine overspeed the use of greater than normal WK^2 for this purpose is questionable. Flywheel effect in excess of normal may lower the generator efficiency since it requires a rotor physically larger than normal with resulting increased windage and thrust bearing losses.

For some installations it may be desirable to incorporate greater than normal WK^2 in the generator rotor. The rotating parts of the turbine are very small and light in comparison to those of the generator, and hence it is not possible to obtain an appreciable increase in the WK^2 of the turbine parts. Any additional WK^2 required must therefore be built into the generator, or incorporated in a separate flywheel. Figure 3 shows the approximate normal WK^2 for generators of various speeds and kva ratings. As in previous additional design requirements, additional flywheel effect will increase the cost of the generator.

On large units of relatively low speed (under 200 rpm) the physical diameter of the generator rotor is relatively large and, since WK^2 varies with the square of the radius, it is possible to design for higher than normal WK^2 without much trouble. For high-speed machines, particularly for speeds above 300 rpm, the rotor diameter becomes small because of the necessity of limiting the centrifugal forces at overspeed. Hence the normal WK^2 for high-speed machines is much smaller than for low-speed generators of the same kva rating. As speed increases, it becomes increasingly difficult to design a generator for higher than normal WK^2. The rotor diameter of low-speed generators is frequently selected to best suit the required WK^2, but on high-speed units the rotor diameter is limited by the centrifugal forces at overspeed.

Powerhouse design for vertical shaft units usually provides for removing the turbine runner and cover plate through the generator stator. It is therefore necessary to make sure that the stator bore is sufficiently large to permit the removal of these parts. This problem is encountered on both high speed and low speed units. On high head Francis type turbines the runner diameter becomes relatively small, but at the same time the maximum permissible generator rotor diameter also becomes small. On large low head propeller type turbines the runner diameter is relatively large and in some cases may require the use of a larger diameter stator bore than would otherwise be used.

The turbine cover plate is greater in diameter than the runner, but when necessary it can be split to permit its removal. In such instances, however, the powerhouse design must provide sufficient space between the turbine and generator to permit the assembly or dismantling of the split cover plate.

Types of hydraulic turbines

Hydraulic turbines may be divided into three general types, each having its own field of application, and each having its own distinctive characteristics. These are the propeller type with either fixed for adjustable blades, the reaction or Francis type and the impulse or Pelton type. Their fields of application overlap to a considerable extent, depending upon the size of the unit and local operating conditions. Generally speaking, however, the propeller turbine is used for heads up to 100 feet, the reaction type for heads up to 1000 feet and the impulse type for heads beyond 1,000 feet.

Propeller

The propeller turbine is similar in principle of operation to a windmill or to a ship's propeller. An adjustable blade, or Kaplan type propeller runner, is shown in Figure 4. The blades may also be cast integral with the runner hub, in which case it is called a fixed blade runner. The Kaplan runner has the advantage of providing automatic adjustment of the runner blade angle to obtain best hydraulic efficiency with varying heads or varying loads.

For heads in the neighborhood of 75 to 100 feet, either a propeller or a reaction turbine might be used. For a given set of hydraulic conditions the propeller unit will have a higher rpm than the reaction turbine, possibly resulting in a lower generator cost. However, other characteristics of the propeller turbine may require special construction of the generator resulting in a higher generator cost even with the higher operating speed.

The runaway speed of a propeller turbine is relatively high, and may be as much as 260 percent of rated speed. The thrust load imposed on the generator thrust bearing is also relatively high, requiring a larger than normal thrust bearing.

Reaction

The most common hydraulic turbine used is the reaction type. The runner for such a turbine is shown in Figure 5. The principle of operation is that of a centrifugal pump operating in reverse. An ordinary centrifugal pump becomes a Francis turbine if water under pressure is supplied to it. The water flow and direction of rotation will be in the opposite direction than when operating as a pump, and it will deliver power to a load.

The runaway speed of a reaction turbine is moderate, usually ranging from 180 percent to 200 percent of rated speed. A generator of normal design will meet the overspeed requirements in most cases.

The thrust load imposed by the reaction turbine is less than that of the propeller turbine but varies somewhat with the head.

Impulse

The third general type used is the impulse turbine. A runner for a typical impulse turbine is shown in Figure 6. The impulse turbine essentially consists of a series of buckets mounted on the periphery of a wheel which is mounted on a shaft. One or more jets of water at high velocity play on these buckets causing the shaft to rotate.

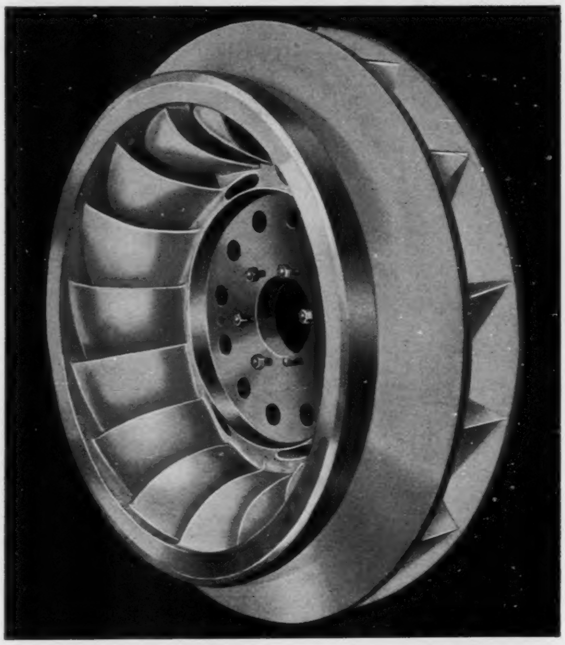
The runaway speed of an impulse turbine is relatively low, usually ranging from 150 percent to 180 percent of rated speed.

When vertical shaft settings are used with impulse turbines, the only external thrust load impulsed on the generator is the weight of the turbine rotating parts, since this type develops no hydraulic thrust.

Vertical and horizontal shaft settings

Most reaction and propeller hydraulic turbines built today are installed with the shaft in a vertical position. This is done for several reasons. In many cases, it is necessary to set the centerline of the turbine runner below normal tail water elevation to prevent cavitation or pitting of the turbine runner. It is sometimes satisfactory to set the runner centerline slightly above the normal tail water elevation.

KAPLAN RUNNER being installed at a low-head hydro-electric plant shows the arrangement of its six propeller blades for variable pitch to suit load conditions. **(FIGURE 4)**



HIGH-SPEED FRANCIS runner for a 36,000-hp, 500-rpm, 800-ft head hydro-electric station shows typical construction. Runner proportions vary for different heads. **(FIGURE 5)**

In many cases during flood conditions in the stream, the tail water elevation may be raised very considerably above normal. If the generator is set at the same elevation as the turbine, it may be necessary to house it in a water-tight building in order to prevent damage by flooding. In most cases, it is more satisfactory to set the generator at an elevation sufficiently high to prevent damage during high water conditions in the tail race. This makes the vertical shaft setting particularly advantageous since the turbine and generator can each be located at their best elevation.

The location of the runner of an impulse turbine with respect to normal tail water is not determined by considerations of cavitation, as in reaction or propeller machines. It may be located at any desirable elevation above tail water, although high settings will result in loss of head and, therefore, loss of power output. In the past this characteristic made it desirable to use horizontal shaft impulse turbines, with resulting lower generator cost.

In addition, vertical shaft settings of impulse turbines were avoided in the past due to difficulties in obtaining good drainage of water from the runner. With the conventional single-jet, horizontal shaft, impulse turbine the jet of water is directed to strike the buckets at a point below the turbine centerline. This permits the water discharging from the buckets to drain without interference into the tail race beneath the turbine. However, it is believed that if such a turbine were set with the shaft in a vertical position, half of the water would be discharged from the buckets in an upward direction, and a considerable portion of this would fall back onto the turbine runner, causing it to operate in a semi-submerged condition with resulting loss in efficiency. Hence, until recently, impulse turbines have been used only with horizontal shaft settings.

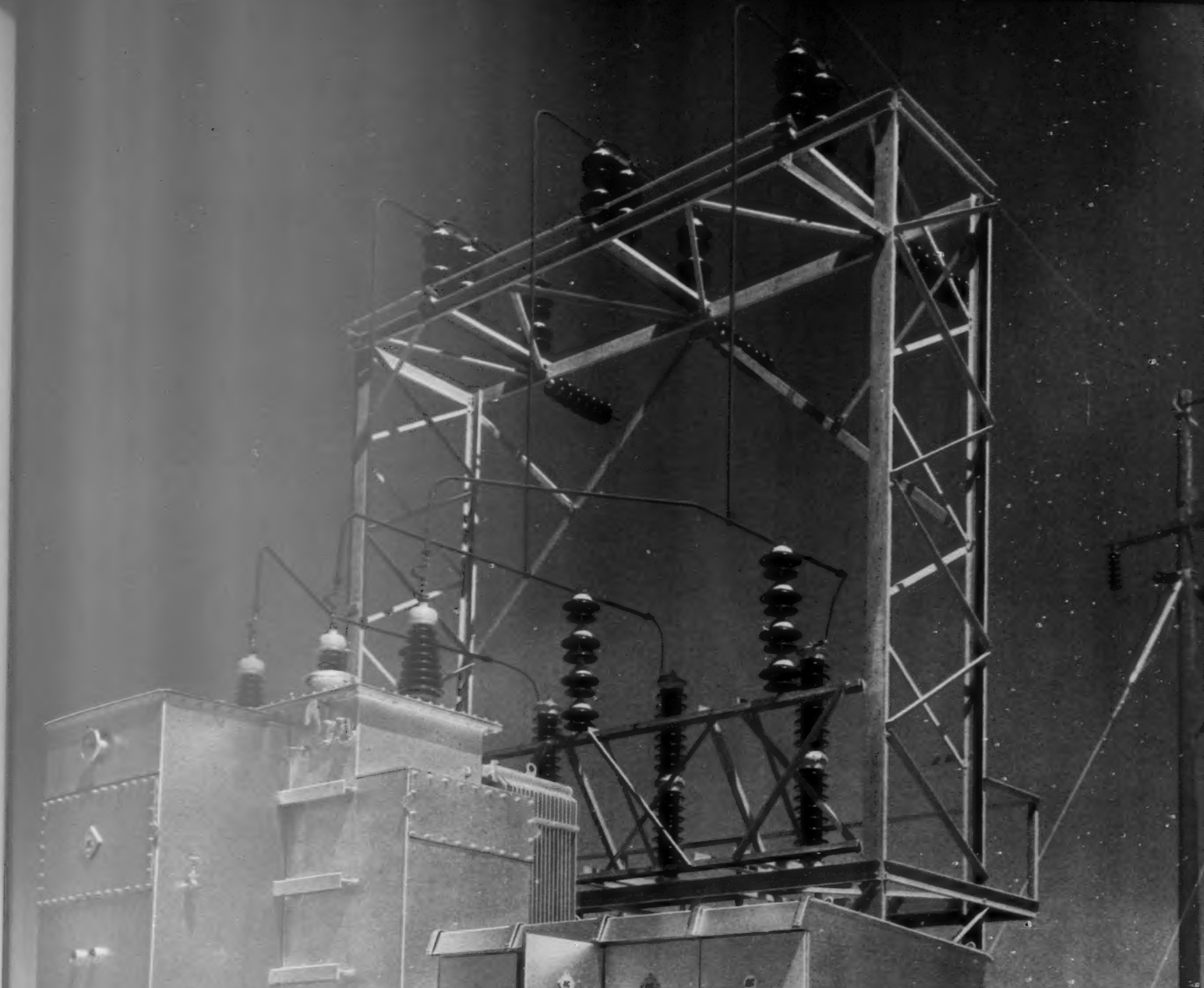
However, in recent years considerable thought has been given to vertical shaft settings, using three or more jets of water with one runner. The use of multiple jets reduces the size of each jet with resulting smaller buckets, and also permits a higher rpm with decreased turbine and generator costs. Model tests have shown that vertical shaft impulse turbines can be designed and built without any particular difficulties, and several such units are now in operation and under construction.

On large, low speed units, vertical shaft setting is more desirable as far as the generator is concerned. Figure 7 shows the stator yoke of a 25,000-kva, 143-rpm, horizontal shaft generator. It is obvious that it is more difficult to design and install such a unit so that the stator will be amply rigid and so that it will remain in a true circle, than if a vertical shaft setting is used, where the stator yoke is supported on the foundation around its entire periphery.

Because of these variable characteristics of hydraulic turbines, it is evident that hydro-generators must be designed to meet the requirements of each individual installation. It is very seldom possible to use a generator designed for one plant for some other installation without major redesign of some or all of the principal parts of the generator, even though the kva rating and speed might happen to be the same in both cases.

IMPULSE RUNNERS and shaft are for a single-jet, 40,000-hp, double-overhung horizontal-shaft hydraulic turbine. Vertical shaft, multi-jet impulse turbines are gaining acceptance for new plants. (FIG. 6)

STATOR YOKE shows the design and construction requirements for a large, horizontal-shaft hydro-generator. Extremely rigid construction is needed to maintain stator in true circle. (FIGURE 7)



ALUMINUM PAINT was used on this 6,000-kva multi-circuit unit substation to reflect New Mexico's scorching sunlight, thereby reducing heat concentration on the unit. Frequent dust and rain storms made it necessary to put special gasketing on compartment doors, sealing them against the elements for additional switchgear protection.

Allis-Chalmers Staff Photo

IS YOUR BEARING TROUBLE A PUZZLER?

by C. D. LAWTON
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Allis-Chalmers Mfg. Co.

BEARING INSULATION placed on the outboard end of a large direct current motor, as pointed out by the author, prevents the flow of potentially dangerous shaft currents through the bearings.

Check bearing insulation first. Defective or inadequate insulation causes shaft currents and subsequent bearing failure.

OCCASIONALLY A PLANT OPERATOR will experience an unusual type of motor bearing trouble, identified by slow pitting, general deterioration and eventual failure. It happens to anti-friction as well as sleeve type bearings. The process may take up to three or four months' time before it is noted. Upon checking, motor alignment and rotor float are found satisfactory, and there is no vibration. The rotor is properly located in its magnetic center. So new bearings are put in, but the same process of bearing deterioration repeats itself. The trouble cannot be explained and the manufacturer is consulted. The trouble — shaft currents.

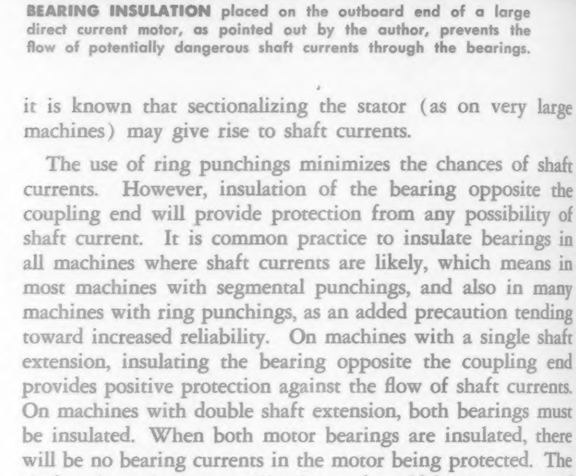
Shaft currents, as the name implies, are currents flowing in the circuit composed of the shaft, bearings, and base (or yoke) of the motor or generator, Figure 1. If of sufficient magnitude, these currents will damage the bearing surfaces, and in severe cases will cause scoring of the shaft and lead to ultimate failure of the bearings. These currents may be of line frequency or some multiple thereof, or may be of slip frequency or some multiple thereof, or may be of both line frequency and slip frequency.

Reluctance of core causes trouble

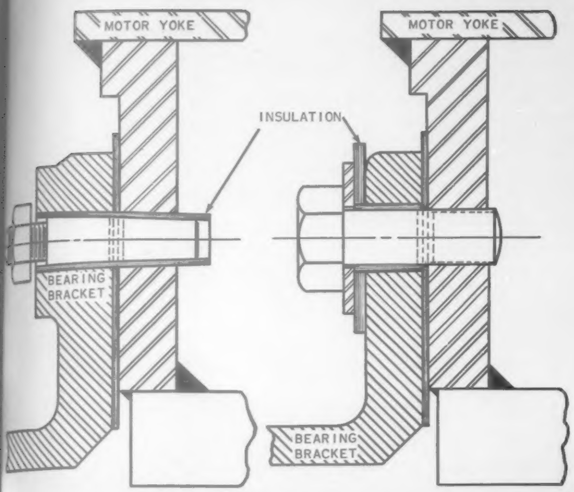
The principal cause of shaft currents is the linking of the shaft by alternating fluxes, due to dissymmetry in the magnetic circuit. Flux from each pole crosses the air gap and, if the magnetic path is symmetrical, will divide equally, half going in a clockwise direction and half counterclockwise. However, if the reluctance of the core is different in one direction than the other, the flux will not divide equally, and there will be a net flux linking with the shaft. Variations in reluctance due to the joints between segments of the stator and rotor core (where segmental punchings are used) are the primary source of shaft currents. Whether or not shaft currents are to be expected depends on the combination of the number of segments and the number of poles. By the same reasoning, it is known that sectionalizing the stator (as on very large machines) may give rise to shaft currents.

The use of ring punchings minimizes the chances of shaft currents. However, insulation of the bearing opposite the coupling end will provide protection from any possibility of shaft current. It is common practice to insulate bearings in all machines where shaft currents are likely, which means in most machines with segmental punchings, and also in many machines with ring punchings, as an added precaution tending toward increased reliability. On machines with a single shaft extension, insulating the bearing opposite the coupling end provides positive protection against the flow of shaft currents. On machines with double shaft extension, both bearings must be insulated. When both motor bearings are insulated, there will be no bearing currents in the motor being protected. The shaft voltage, however, still exists and could be the source of damaging effects in the bearings of the connected machines.

The voltage which causes the shaft current appears across the ends of the shaft. Insulating the bearing presents an open circuit to this voltage, and therefore no current can flow. The



SHAFT CURRENT FLOW of a pedestal bearing motor is shown in color. A bracket or housing bearing machine would have similar current flow, except through the bearing supports or brackets and stator yoke. **(FIG. 1)**



ONE METHOD OF BREAKING shaft current circuit sometimes used on bracket or housing bearing machines is shown above. It has the disadvantage of being subject to shorting by dirt, oil and painting. **(FIGURE 2)**

oil film between the babbitt and the journal insulates the bearing to a degree, but it may take only a fraction of a volt to break down the oil film, and cause the intermittent electric discharges from the babbitt to the shaft. Such electric discharges may occur at a rapid rate in many places along the shaft journal at nearly the same time. The amount of current which would flow is affected by the type of oil being used in the bearing and the thickness of the oil film during operation.

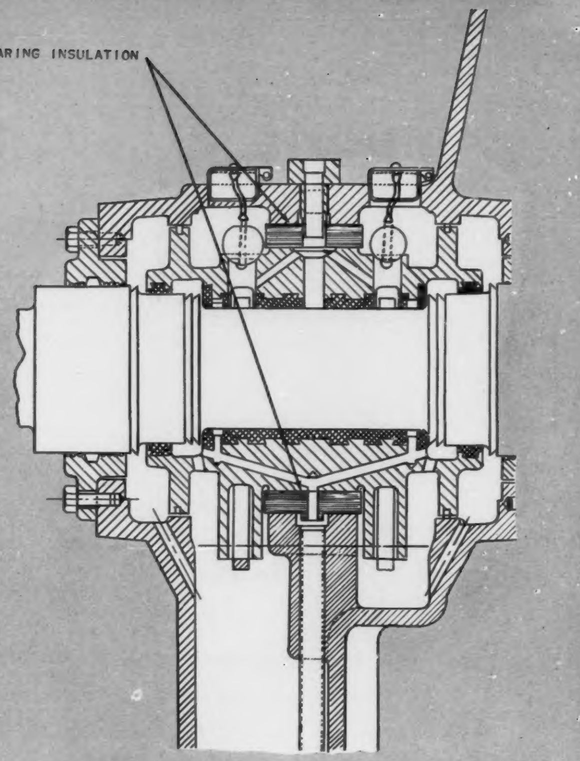
Proper bearing insulation helpful

Bearing insulation is accomplished in a number of ways. On a bracket bearing machine, insulation can be obtained by using a material such as fish paper between the motor housing and the yoke, as shown in Figure 2. With this method the insulation is exposed to short circuit by lead base paint, which might be used in repainting the machine. Another method more commonly used, shown in Figure 3, is to insulate the bearing bushing itself from its support. This is done by using a fabric base phenolic material which would support the bearing bushing within the bearing enclosure. It would then not be exposed to accidental shorting. On pedestal bearing machines an insulating pad is placed underneath the bearing pedestal itself.

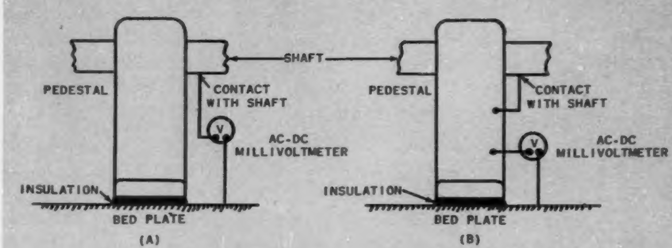
With all types of bearing insulation, one must be careful to determine that the bearing is not grounded by some unsuspected dowel pin, oil pipe, forced-feed oil lubrication system, or possibly a chain securing the cover for the oil ring inspection holes.

If it is suspected that a motor or generator has bearing trouble due to shaft current, a check may be made as follows: On a machine without insulated bearings, such as the smaller bracket bearing variety, take dc millivolt readings between each end of the shaft and yoke. Also take readings from one end of the shaft to the other. If any voltage readings of about .01 or higher are obtained, shaft currents are likely to cause trouble. Where bearings are insulated, proceed as shown in Figure 4. If this test shows defective insulation, it will be necessary to make further tests as shown in Figure 5 to determine whether the defect is in the oil piping, or in the pedestal, or in the bracket insulation.

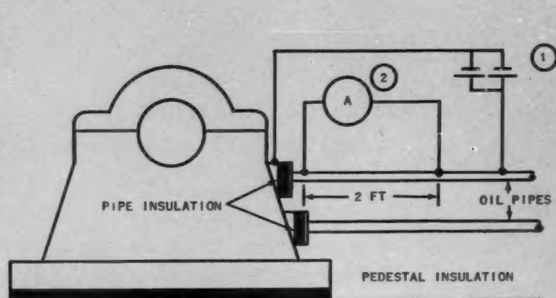
Once the source of the trouble has been located, it can usually be remedied quite simply.



BETTER INSULATION can be obtained by insulating bearing bushing itself on the inside of the bearing enclosure, as shown above. This type of insulating has replaced older method shown in Figure 2. **(FIGURE 3)**



BEARING INSULATION can be checked while machine is running by comparing readings A and B. If they are the same, insulation is satisfactory. Insulation is defective if readings at B are lower than at A. **(FIG. 4)**



1 TWO DRY CELLS OR ONE STORAGE BATTERY
2 AMMETER FOR USE WITH EXTERNAL SHUNT.

TWO DRY CELLS or storage battery (1) and an ammeter (2) with an external shunt can be used to check bearing insulation when machine is in operation. If ammeter needle moves, insulated joint is defective. **(FIG. 5)**

ADJUSTING VERTICAL THRUST BEARINGS

EQUAL LOAD DISTRIBUTION on thrust bearing shoes and correct shaft alignment increase efficiency and reduce wear and maintenance on vertical shaft generators. This 8400-kva, 225-rpm unit is installed at a Rocky Mountain hydro-electric station.

by J. E. PETERMANN*
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Allis-Chalmers Mfg. Co.

Tried and proven method assures proper adjustment of adjustable bearings and alignment of shafts in vertical hydro-generator installations.

VERTICAL SHAFT ALTERNATORS driven by hydraulic turbines have become increasingly prominent in harnessing the energy of stored water. It is only natural, therefore, that such valuable equipment should be given every consideration for improvement in design and operation. Design improvements usually result in smaller units of higher output at a higher speed. The progressive designs have also brought about many improved methods of installing modern hydro-electric units.

One of the most important requirements of the installation procedure is to see that the thrust bearing shoes are equally loaded and that the shaft is plumb. While this subject is not entirely new, the proposed method of alignment is readily usable for adjusting thrust bearings and plumbing shafts of vertical hydro-electric units.

This adjustment procedure assures smooth running units, and the saving in maintenance and wear of machine parts more than warrants the small amount of time and expense incurred in applying the method when installing a hydro-electric unit.

Check elevation, load and plumb

Adjustable pivoted-shoe type thrust bearings are commonly used in large vertical hydro-electric units to support the hydraulic load plus the weight of the rotating parts. The bearing shoes are individually pivoted upon the rounded heads of jack screws threaded into the bearing base. Jack screw adjustment is obtained by:

1. Locating shaft at the correct elevation.
2. Adjustment of the bearing shoes to obtain equal loading on all shoes. With improper adjustment some shoes will support excess load, a condition that might lead to bearing trouble.
3. An additional adjustment is made to swing the shaft to a vertical (plumb) position without disturbing the uniformity of the adjustment completed in step 2. In process of ascertaining the deviation of the shaft from the vertical, the runout at the lower end of the shaft can be checked and the causative residual error at the thrust bearing runner can be determined.

The use of proper tools aids adjustment. In addition to a striking wrench and sledge, a gauging wrench and a circular scale (Figure 1) should be provided. The gauging wrench, made of material about one-quarter inch thick, should fit the adjusting screw head snugly without backlash. Buttons or blocks on the under side of the wrench jaws support the jaws in engagement with the screw head. The wrench handle is offset or "goosenecked" to permit it to slide on the bearing housing floor. One edge of the wrench handle should be straight and smooth. A scale, cut from sheet brass, is made to the largest, convenient radius from the center of the jack screw for maximum accuracy. A mark is scribed on the gauge wrench handle at radius of the scale.

Screws adjusted and checked individually

The screws are adjusted up or down with a sledge and a striking wrench until the shaft is at the correct elevation and the screws seem to be uniformly tight. These are the initial "sledged-tight" positions of the screws. Each screw is numbered and its angular position is marked by applying the gauge wrench and scribing a line on the floor of the housing along the edge of the wrench. Taking one screw at a time, it is backed off until it is free of load, and then with a hand wrench it is turned upward until it begins to take on load. This is the "hand-tight" position which should be marked in

*Author wishes to thank Mr. W. F. King, Dynamatic Corp., Kenosha, Wisconsin, for his help in preparing this article.

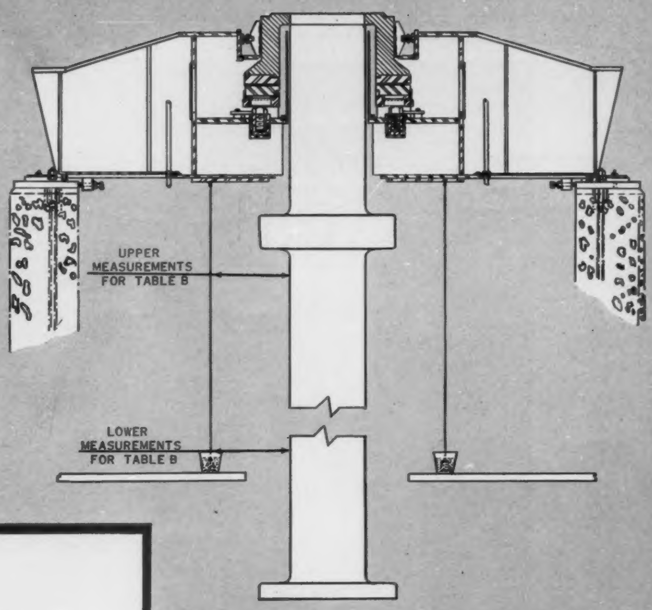
the same manner as the "sledged-tight" position. The distance between these marks, measured at the scale radius, is the "forced arc," sometimes called the "slugged arc." Better accuracy can be obtained by rechecking the "hand-tight" position a few times. In the absence of a circular scale the chord may be measured with a straight rule, with a slight loss in accuracy.

After measuring the "forced arc" the screw is replaced exactly in its "sledged-tight" position. This procedure is repeated with each screw and the correction to equalize the arcs is determined as shown in Table A. The correction for each screw at the gauge radius is:

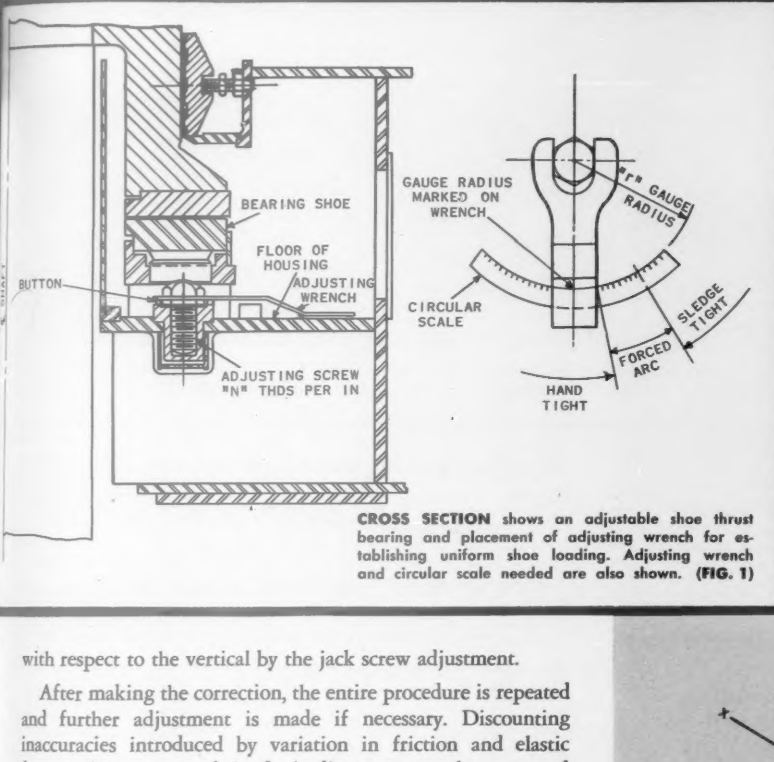
$$\left(\frac{n-1}{n} \times \text{difference from average arc}\right)$$

where "n" is the number of screws or bearing shoes.

This adjustment factor holds true if the shaft is not tipped



DRAWING REPRESENTS a typical set-up needed to check a shaft to determine whether it is plumb and to measure runout. Data contained in Table B can be obtained from this measurement set-up. **(FIGURE 2)**



CROSS SECTION shows an adjustable shoe thrust bearing and placement of adjusting wrench for establishing uniform shoe loading. Adjusting wrench and circular scale needed are also shown. **(FIG. 1)**

with respect to the vertical by the jack screw adjustment.

After making the correction, the entire procedure is repeated and further adjustment is made if necessary. Discounting inaccuracies introduced by variation in friction and elastic factors, the accuracy of the final adjustment may be expressed by:

$$\frac{a}{1/n} = \frac{d}{2\pi r}$$

$$a = \frac{d}{2\pi r n}$$

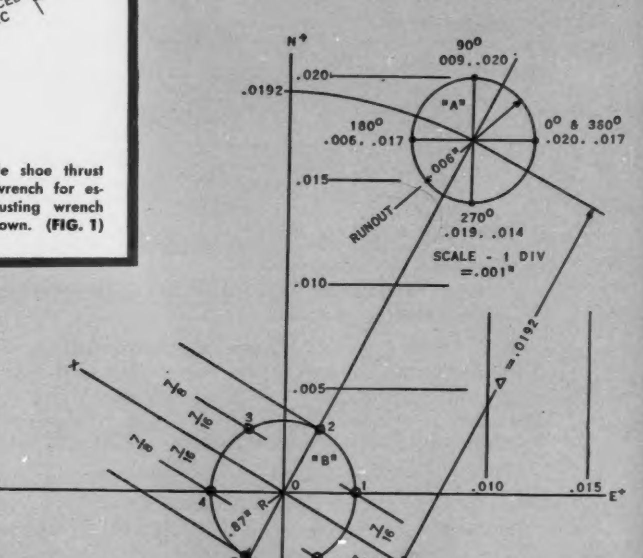
where

a=Accuracy of adjustment

d=Maximum difference from average arc

r=Radius from center of screw to measured arc

n=Number of threads per inch on screws



GRAPHICAL DETERMINATION of shaft runout and bearing adjustment to plumb shaft uses data of Table B. Amount each shoe must be lowered or raised becomes obvious when these values are plotted on chart with NESW directions noted, with bearing shoe positions properly located. **(FIGURE 3)**

GENERATOR AND TURBINE shafts must be correctly machined and properly coupled. Coupled shafts are shown being inspected and checked by inspectors to rigid standards for correct alignment prior to being shipped for assembly. Shafts are for a 30,000-kva, 75-rpm hydro unit.

For example if $d=.1''$, $r=18''$, $n=4$

$$a=\frac{.1''}{2\pi\times18\times4}=.00022''$$

Plumbing shaft

After the shoe loading is adjusted as described, the shaft must be plumbed and checked for runout. Both steps are combined in the following procedure:

First, four plumb lines are suspended from the lower bearing housing, or other convenient support, and spaced 90 degrees apart around the shaft as shown in Figure 2. The plumb lines should consist of steel music wire supporting heavy finned weights, which are immersed in pails of oil to prevent wires from swaying and twisting.

Then, micrometer measurements are taken from the shaft to the wires at two elevations as widely separated as possible. The shaft is then rotated 90 degrees, 180 degrees, and 270 degrees and the measurements are listed as shown in Table B. In practice it is well to take check readings after a complete 360-degree revolution. For accurate readings the micrometer should be equipped with battery and ear phones.

Difference between each upper and lower reading is determined as shown in Table B. Next, the one-half net difference between each set of opposing readings is determined. In the example given in the table, the east and west readings form one set, the north and south the other. (Note that the subtraction is done algebraically, i. e.)

$$N-(-S)=N+S$$

Then, as shown at A in Figure 3, the half differences from Table B for each quarter turn of the shaft are plotted on cross-ruled paper. Positive values are plotted along N and E axes; negative values, S and W. The points thus plotted fall on a circle, the diameter of which represents the shaft runout in the length L, Figure 2. Total runout will be in proportion to the diameter of circle A as the total shaft length below the thrust bearing is to the length L.

The location of the center of circle A with respect to the origin (the point of intersection of the axes) is the amount in length L and in direction that the shaft is out of plumb.

Results secured from the plumb line measurements are not affected by:

1. Plumb lines being unequally spaced from the shaft.
2. Removing and replacing plumb lines when turning shaft.
3. Shaft shifting within bearing clearance when it is turned.
4. Upper and lower measurements being at different shaft diameters.

Bent shaft poses problem

However, if the shaft is bent, the results will be incorrect. To check the shaft for straightness, the distance from plumb lines to the shaft is checked at a series of measured elevations in two perpendicular directions. A shaft which is straight but out of plumb will show measurements which will be directly proportional to the distance from the thrust bearing surface.

After establishing the amount and direction in which the shaft is out of plumb, the next step is to readjust the thrust bearing to swing the shaft to a vertical position without changing the equal load distribution on the bearing shoes.

The change in the adjustment of the jack screws to accomplish this can be easily determined graphically as shown by diagram B of Figure 3.

Circle B is drawn with its center at the origin.

$$\text{The radius of circle } B = \Delta \frac{R}{L} 2\pi r n$$

where Δ is the amount the shaft is out of plumb in the distance L between the upper and lower shaft measurements,

R is the radial distance from the shaft center to the jack screw circle.

In the example, radius of circle B is expressed as:

$$\text{Radius of circle } B = .0192'' \times \frac{15}{150} \times 2\pi 18 \times 4 = .87''$$

The jack screw positions are located on circle B with respect to the N—S and E—W axes. A line X—X is drawn through the origin perpendicular to line Y—Y which passes through the center of circle A. The perpendicular distance from a jack screw position on circle B to line X—X is the adjustment necessary for that shoe as measured on the "forced arc" scale at the same radius used in initially adjusting the screws. The direction of adjustment needed to plumb the shaft is:

Jack Screw 1 ....7/16 inch down
Jack Screw 2 ....7/8 inch down
Jack Screw 3 ....7/16 inch down
Jack Screw 4 ....7/16 inch up
Jack Screw 5 ....7/8 inch up
Jack Screw 6 ....7/16 inch up

Inaccuracy at the thrust bearing, that is, the deviation of the rotating surfaces at the thrust bearing, from being perpendicular to the shaft can be expressed by:

$$\text{Inaccuracy} = \text{Measured runout} \times \frac{D}{2 \times L}$$

where the inaccuracy is across the thrust bearing runner at diameter D and the runout is measured on circle A of Figure 3.

In the example, assuming a thrust bearing diameter D of 37 inches;

$$\text{Inaccuracy at thrust bearing} = .006'' \times \frac{37}{2 \times 150} = .00072'',$$

which is within practical limits.

Of course, runout at the lower end of coupled shafts can be caused by error at the coupling surfaces. This can be isolated by checking the shafts for straightness as described previously.

TABLE A

Screw No.	Forced Arc Inches	Difference From Average	Correction 5/6 of Difference
	7.5	+.9	Lower .75
	5.9	—.7	Raise .58
	6.9	+.3	Lower .25
	6.3	—.3	Raise .25
	7.3	+.7	Lower .58
	5.7	—.9	Raise .75
Total	39.6		
Average	6.6		

ACTUAL MEASUREMENTS of forced or slugged arc for a six-shoe bearing and the amount of correction necessary to establish uniform shoe loading are shown in tabular form.

TABLE B

Position		Measurements: Whole Inches May Be Omitted		Differences				
		Upper	Lower	Upper Minus Lower	N — S	Plot (N — S)/2	E — W	Plot (E — W)/2
0°	N	.477	.460	.017	.034	.017		
	S	.834	.851	—.017				
	E	.248	.235	.013			.024	.012
	W	.751	.762	—.011				
90°	N	.468	.448	.020	.040	.020		
	S	.086	.106	—.020				
	E	.628	.619	.009			.018	.009
	W	.518	.527	—.009				
180°	N	.136	.119	.017	.034	.017		
	S	.329	.346	—.017				
	E	.532	.527	.005			.012	.006
	W	.736	.743	—.007				
270°	N	.407	.393	.014	.028	.014		
	S	.863	.877	—.014				
	E	.101	.091	.010			.018	.009
	W	.105	.113	—.008				
360°	N	.805	.788	.017	.034	.017		
	S	.334	.351	—.017				
	E	.158	.146	.012			.024	.012
	W	.606	.618	—.012				

Radius of jack screw circle, R = 15 inches
Vertical distance between points of measurement, L = 150 inches
Forced arc gauge radius, r = 18 inches
Number of threads per inch on jack screws, n = 4 inches

DATA SHOWN is obtained by following procedure described under "Plumbing Shaft" section on page 32. Data obtained in first two columns is worked to values which can be plotted in Figure 3.

METAL-CLAD SWITCHGEAR

by H. H. ACKMANN
Switchgear Section
Allis-Chalmers Mfg. Co.

Today's metal-enclosed switchgear provides a standard, extremely flexible means of controlling power station auxiliaries.

CONTROLLING POWER PLANT AUXILIARIES with metal-clad switchgear has become accepted practice in modern power plant operation. Some of the credit for the dependable and continuous service provided by today's power plants must be given to the metal-enclosed, removable circuit breaker, its associated copper-insulated bus and connections. The designer of a switchgear arrangement for a power plant has available many advantages offered by the factory-assembled, metal-clad switchgear. With this in mind, there are several important factors that should be taken into account before metal-clad switchgear is applied in a power plant.

One of the first functions of auxiliary switchgear is to maintain a source of energy for the power plant and its auxiliary equipment. Before the first motor in the plant starts to move, power must be available for lights and other vital needs. Consequently, provisions must be made to obtain energy through interconnection to another station, another system, or some standby source of energy, such as a diesel-driven generator built into the plant. Once the station is in operation, energy for the auxiliary equipment is furnished by the station generating equipment. Flexibility should be built into the switchgear to assure constant energization of the bus.

To assure a constantly energized bus, automatic switching equipment should be built into the switchgear. By using potential transformers on the incoming power sources and providing undervoltage relays, various schemes of automatic switching can be worked out to make power available at all times.

Duplication provides added protection

In designing a dependable arrangement for auxiliary power a bus failure has to be considered as a possibility. With the bus completely insulated and enclosed in a steel cell, this problem of a bus short has become rather remote; but nevertheless, it is best to have more than one bus so that energy will be available in the event that trouble occurs. Following the practice of having duplicate pumps, drives, mills, etc., proper switchgear design has one of the units connected on the main bus while the other, the stand-by unit, is fed from the reserve, or emergency bus. In this way, even though one bus (one group of switchgear) is in trouble, the essential pumps and mills can be run during the emergency from the other bus. Consequently, two or more groups of metal-clad switchgear associated with each prime mover and its generator is a rule rather than the exception in a modern power plant.

The four typical single-line diagrams of four different power plants shown in Figures 1, 2, 3, and 4 illustrate the variety of arrangements used for maintaining a continuous source of energy.

Figure 1 shows a duplicate bus scheme used in a medium size power plant. Examination of this single-line diagram reveals that it has two auxiliary transformers, each feeding a bus. Primaries of the transformers are fed directly from the main station bus. With this arrangement the control can be set up so that there would be an automatic transfer of power source if one of them fails. In this case, the transfer would be from "A" to bus "B," or vice versa, depending upon which bus the transformer has been set up to carry the load under normal conditions. Usually, the control is arranged so that the operator can select the transformer that he wants to carry this auxiliary load. Ordinarily the load is changed from time to time so that one transformer is not subject to more severe duty than the other.

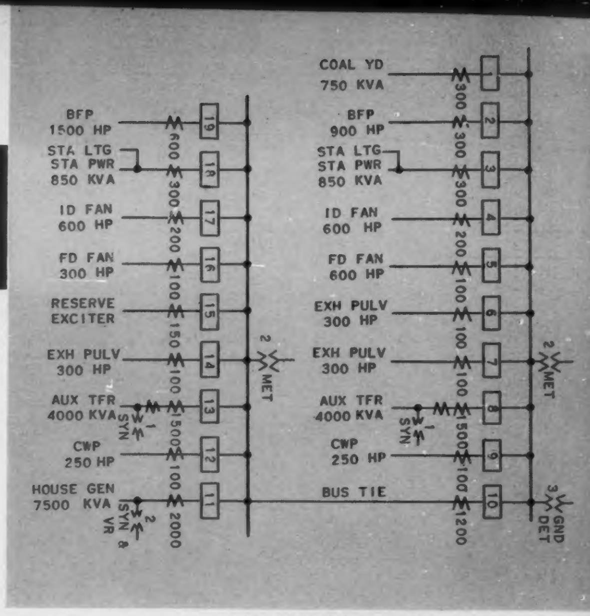
In this particular power plant, a 7500-kva house generator is provided for furnishing the power for starting the plant. It also can be used for furnishing all of the power required by the auxiliaries. In this arrangement, two groups of auxiliary switchgear can be energized from three separate and independent power sources.

The single-line diagram shows that this arrangement has duplication of boiler-feed water pumps, station lighting and service, induced draft fans, forced draft fans, pulverizer motors, and circulating water pumps. A spare circuit breaker should be available for emergency periods when one of the circuit breakers needs to be serviced. The regular breaker could be replaced readily with the spare breaker, and the particular auxiliary motor could be stopped to make the change. Since the change would take approximately three to five minutes, it would not be necessary to start the duplicate unit, except in the event of an essential operation when the duplicate unit could carry on during the change.

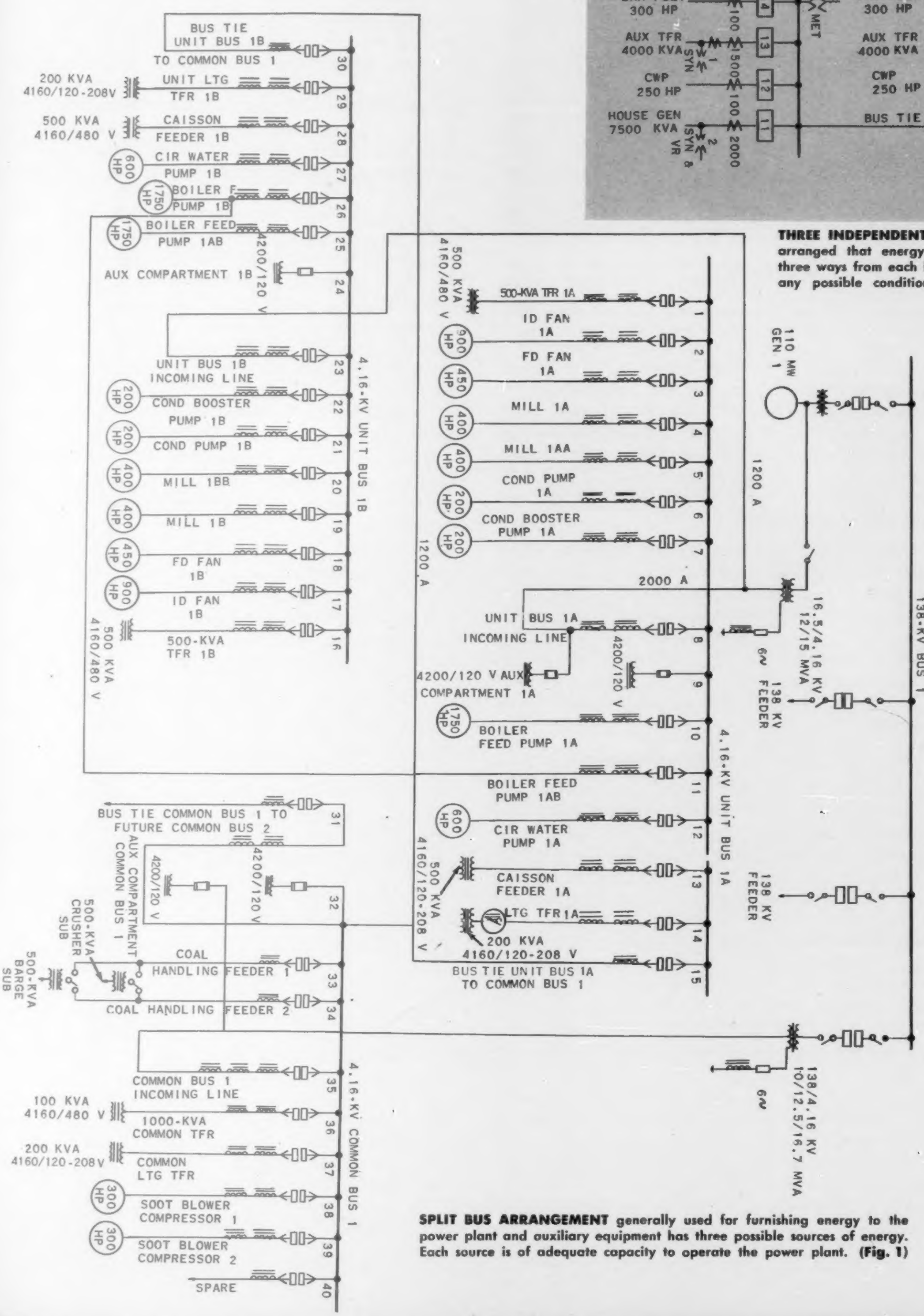
Interconnections protect unit system

Typical arrangements for the so-called unit system of power generation are shown in Figures 2 and 3. Under normal conditions, the auxiliary power is drawn from a tap on the main generator leads. It is stepped down to 2400 or 4160 volts through an auxiliary transformer and fed through a circuit breaker to a common group of switchgear units. Two other groups of switchgear can be fed from this group through a common circuit breaker.

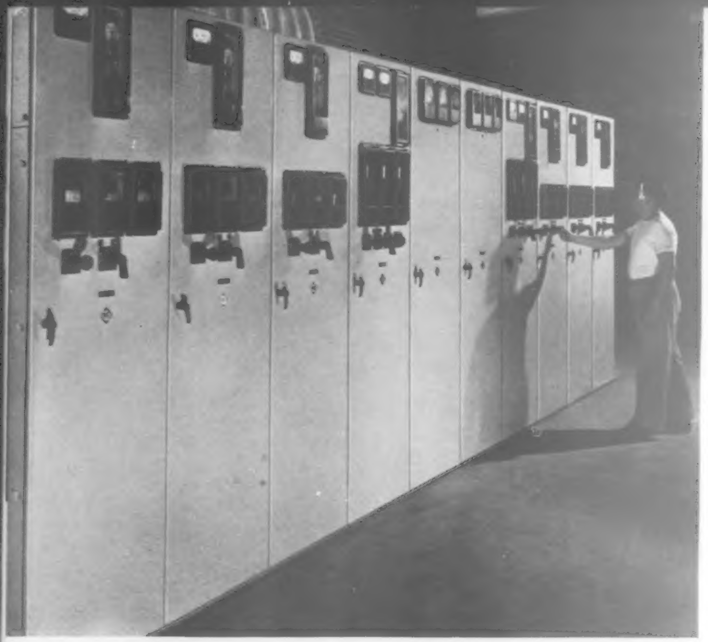
Power Plant Auxiliaries



THREE INDEPENDENT bus sets are so arranged that energy is available in three ways from each bus under almost any possible condition. **(FIGURE 2)**



SPLIT BUS ARRANGEMENT generally used for furnishing energy to the power plant and auxiliary equipment has three possible sources of energy. Each source is of adequate capacity to operate the power plant. **(Fig. 1)**



WATTHOUR METER plus normal complement of meters and relays comprise six standard feeder units in this switchgear. Two of four center sections are standard circuit breaker units with directional overcurrent relays replacing standard ones, and an additional voltmeter and switch. Other two sections are auxiliary cubicles housing potential transformers.

As long as the generator is in operation, power is available to all of the switchgear. In starting the plant or under emergency conditions, power is available through the auxiliary power transformer tapped off the main 138-kv bus. Because energy can be brought into each bus in several different ways, it is almost impossible to lose auxiliary power with this type of bus-tie breaker arrangement.

Here again duplication of auxiliary equipment is used so that, if any one bus is in trouble, the power plant can continue in operation by using the auxiliaries connected to one of the other groups of switchgear. When one or two spare breakers are available, the circuit breaker maintenance problem is minimized. Under almost all conditions, a feeder can be taken out of service long enough to allow the racking down and removal of the breaker that is to be worked on, and the racking in of the spare unit.

Large plant protection is more elaborate

Figure 4 shows the arrangement of auxiliary equipment in a large power plant. Here again special precaution has been taken to provide interconnections so that the possibility of losing power for the operation of the auxiliary equipment is almost impossible. Normally, the energy for the auxiliary equipment would be taken from the main station bus by a step-down transformer. More than one of these station auxiliary transformers would be located at the power plant. Interconnections between groups of auxiliary switchgear make it possible to energize any or all of the groups from each transformer. In this way, power would be available in the station at all times as long as the main bus was in order. Since this bus has a sectionalizing circuit breaker, whatever trouble came along would be isolated.

In the design of switchgear for power plant auxiliaries the standard units of metal-clad equipment should be used as much as possible. With this in mind, each of the types of circuits will be considered with respect to using a standard unit with some modifications.

The incoming circuit from the power transformer can be a standard feeder unit with some additional auxiliary equipment. The standard feeder unit consists of an electrically operated circuit breaker with its associated current transformers, overcurrent relays, ammeter, and ammeter switch. The circuit breaker is controlled by a control switch mounted on the front of the panel and the position (open or closed) is indicated by red and green lights. The relays, ammeter, and the ammeter switch are also on the panel.

On the incoming circuit, voltage indication on the panel is necessary in order to determine whether the circuit is energized before the breaker is closed. The addition of a voltmeter to provide the essential indication requires a set of potential transformers which can be mounted in a superstructure atop the standard feeder structure. To prevent excessive damage to the transformer, a set of differential relays, mounted on this incoming breaker section, should be added to trip the circuit breaker if a fault occurs in the transformer. One of the two sets of current transformers required for differential protection can be placed in this circuit breaker structure. For simplicity, double secondary current transformers normally are used when differential protection is furnished.

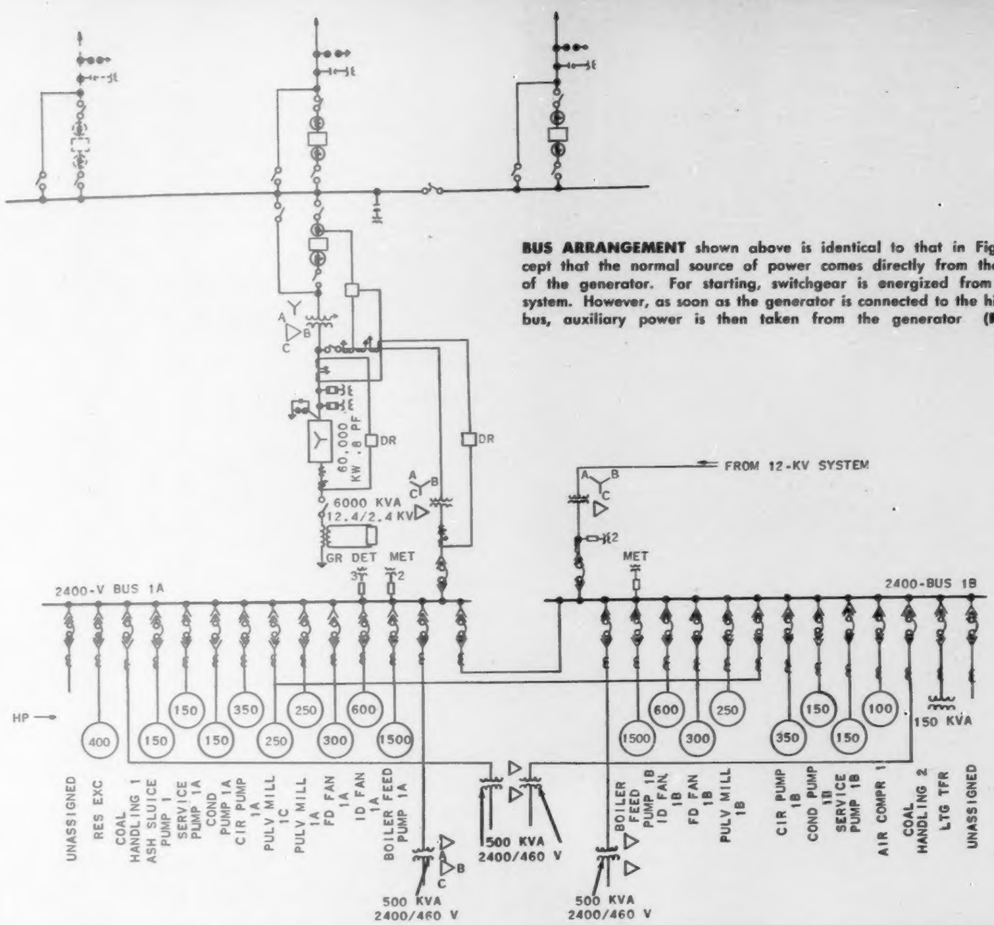
The incoming line is usually equipped with a watt-hour meter for integrating the amount of power that is fed into the auxiliary equipment. The current coils, like the ammeter, are connected to the same set of current transformers. The potential for the watt-hour meter, however, is taken from the potential transformers connected on the incoming side of the circuit breaker.

When some sort of automatic switching is built into the incoming power source, the undervoltage relays which are mounted on the panel of this incoming breaker section are connected to the same potential transformers as the meters.

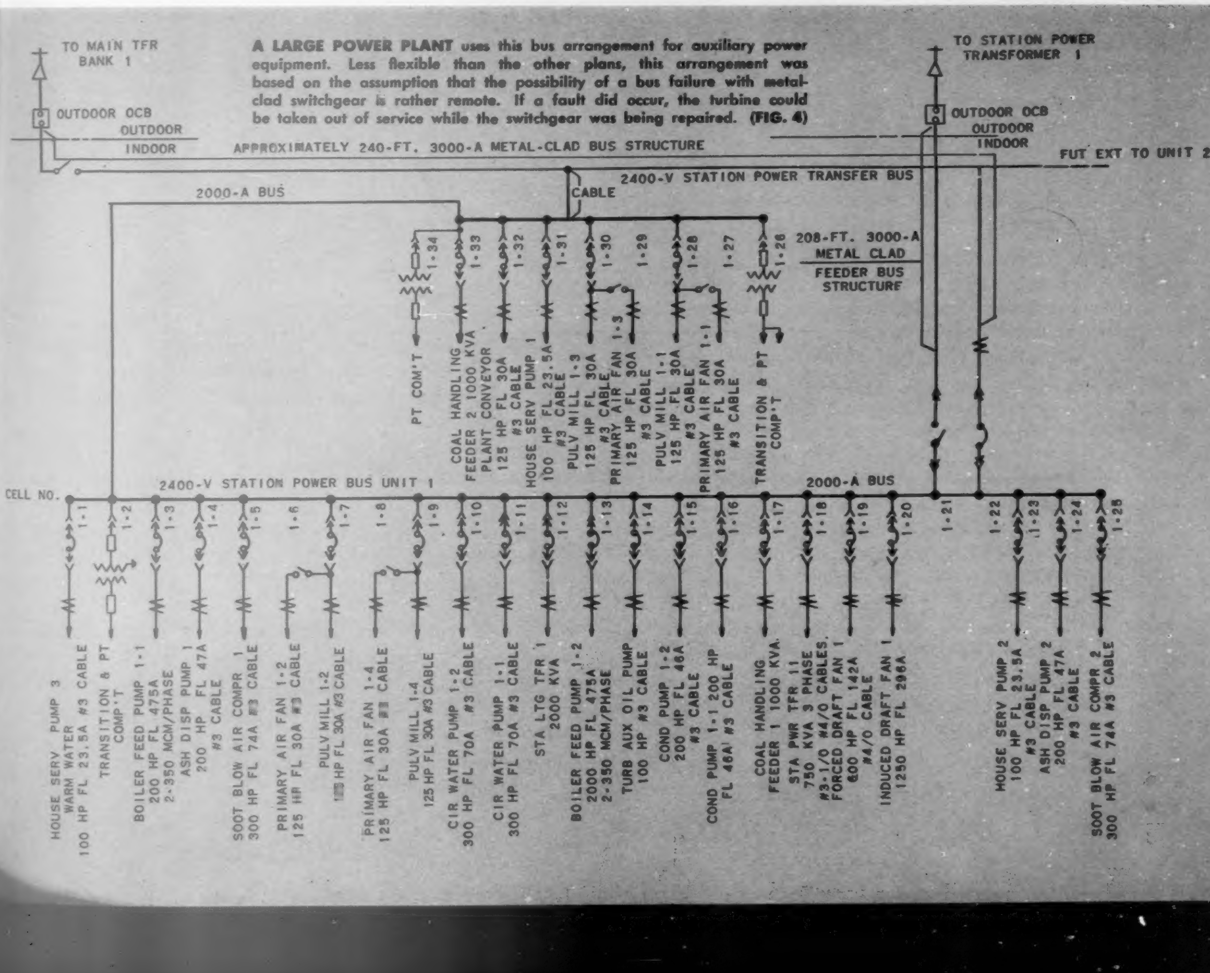
Power for light and other 120/230-volt requirements in the power plant is usually taken from the auxiliary switchgear. In this way, the same reliability can be had for the station lighting circuit as there is for the auxiliary equipment. This particular feeder circuit is equipped with a standard breaker section having current transformers. overcurrent relays, ammeter, and ammeter switch with the circuit breaker control switch and its indicating lights. A watt-hour meter is usually included on this feeder unit, for the amount of power consumed through it is generally required by the power plant records. The 480-volt requirements for the power plant are sometimes met through the same circuit breaker as the station lighting. If, however, a separate circuit breaker section would appear to be advantageous, it could be added and should have the same complements of relays and instruments as the station service breaker section.

Type of protection determines unit choice

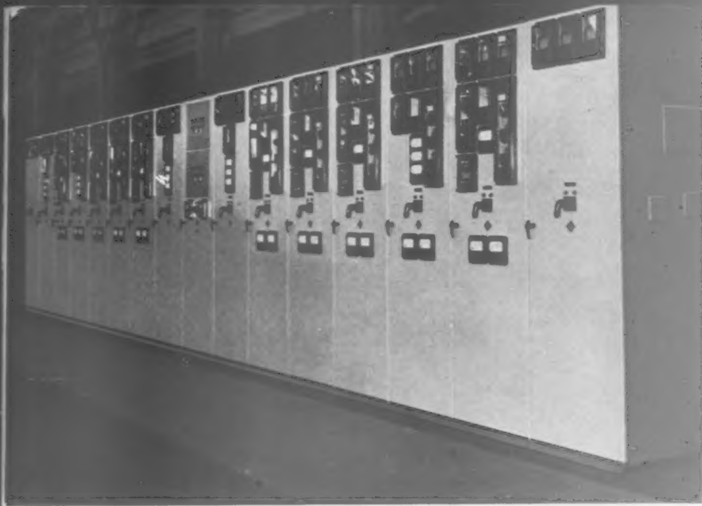
These same basic or standard circuit breaker sections are used for the motor feeder circuits, although some variations can be built into a unit to take care of the particular requirements of a motor circuit. First, it must be determined as to what sort of protection is to be obtained by the circuit breaker section; that is, will full motor protection have to be built into the circuit breaker unit, or will short-circuit protection be sufficient? There seem to be differences of opinion as to what the relaying should be for the auxiliary motors. Some engineers insist that there should only be short-circuit protection so the circuit breaker will have no reason to open except when there is a short circuit. Their argument follows the premise that the



BUS ARRANGEMENT shown above is identical to that in Figure 1, except that the normal source of power comes directly from the terminals of the generator. For starting, switchgear is energized from the 12-kv system. However, as soon as the generator is connected to the high voltage bus, auxiliary power is then taken from the generator **(FIGURE 3)**



A LARGE POWER PLANT uses this bus arrangement for auxiliary power equipment. Less flexible than the other plans, this arrangement was based on the assumption that the possibility of a bus failure with metal-clad switchgear is rather remote. If a fault did occur, the turbine could be taken out of service while the switchgear was being repaired. **(FIG. 4)**



MOUNTING RELAYS instead of indicating meters at top of panel was specified for this installation. Consequently, all meters were mounted at or below eye level. Two annunciator panels that indicate the position of remotely mounted equipment are located in the center of the switchgear.

motor should continue to operate even though it is overloaded because the consequences of having a fan or pulverizer stop may be more serious than those arising from an overheated motor.

For example, if during emergency pumping conditions the boiler feed pump drive motors should become overloaded, it would be quite possible to allow the motor to continue to run at this overload long enough to permit the operator of the power plant to shift the load on the plant to some other station or machine so that the boiler or boilers fed by the faulty pump could be taken out of service.

If the circuit breaker on the motor circuit had tripped when the motor became overloaded, considerable boiler damage might have been caused. In many cases, even the cost of rewinding the motor might be considerably cheaper than a damaged boiler.

Instantaneous overcurrent relays furnished on the switchgear will take care of faults on the feeder circuit. However, if more protection is wanted, other types of relays must be used. In order to get satisfactory characteristics for controlling a particular circuit, it is sometimes necessary to use a combination of two types of relays.

The time current characteristic curves of the induction time overcurrent relay meets most feeder circuit requirements. For the motor feed circuit, however, it is not always possible to match the motor time current characteristics with the relay inverse-time current curve. If a suitable overcurrent relay can be selected to give the long time protection required, this same relay can be equipped with an instantaneous attachment for quick tripping under fault conditions. For motor feeder circuits, thermal relays can be used. In general, the time current characteristics of the thermal relay comes closer to matching most motor requirements than the inverse-time overcurrent relays. Thermal relays are available with instantaneous attachments. With a thermal relay of this type, the overload protection required for the auxiliary motors is provided by the thermal element in the relay. Short circuit or fault protection is obtained by the instantaneous overcurrent unit built into the relay. The trend seems to be in the direction of the thermal relay and away from the inverse time overcurrent relay. The swing may be accelerated somewhat when thermal relays are equipped with temperature compensation.

Any of these basic relaying schemes can be supplemented with additional relays which can be used to trip the circuit breaker, or just connected to some sort of an alarm. When an alarm scheme of this type is used, the operator is warned when a motor is overloaded or in trouble, so the machine can be taken out of service before it is subjected to serious damage.

There are numerous factors that indicate what method of motor protection shall be used. Some motor installations require one type of protection, while other motor installations of the same size in the same power plant may dictate use of the other type.

Standard units are versatile

Built into the standard switchgear unit is a set of auxiliary switches mounted on the circuit breaker. These are designed to be used in control circuits. The auxiliary switches make it possible to electrically interlock various circuit breakers which, for example, could be arranged so that it would be impossible to close a forced-draft fan circuit breaker before the induced fan breaker is closed; or if under fault conditions one circuit breaker trips, it would automatically close a similar unit on another bus. The number of circuit breakers included in an interlocking scheme depends entirely upon what protective steps are necessary to safeguard the satisfactory operation of the power plant.

The circuit breakers furnished in the metal-clad switchgear used in the four diagrams have ten auxiliary switches. Ordinarily, this will provide all of the normally open and normally closed contacts required for a suitable interlocking scheme for a power plant. Should more contacts be required, they could be added by means of a multiple-contact auxiliary relay.

Circuit breakers can be controlled in two ways. The larger size power plants have the major control in the operating room, so the switchgear for the auxiliary equipment is controlled from the same place. Sometimes a control switch called a permissive switch is also put on the switchgear to enable anyone to trip the circuit breaker. The circuit breaker can be closed only from the control remote from the switchgear. The permissive contact, however, must be closed on the control switch on the switchgear before the remote switch will close the breaker.

Indicating lights are usually put on the switchgear, even though it is controlled from some remote station. The control switch in the operating room would also have indicating lights with this arrangement.

In some power plant arrangement it may be more convenient to have all control and metering of the auxiliary equipment located on the panels of the metal-clad switchgear. This arrangement is much easier to install and naturally is more economical.

If some handy location can be worked out for the switchgear so the panels can be used for the control board, there is no need for the added expenditure of a separate control board.

The design of metal-clad switchgear allows for considerable flexibility in arrangement and control. However, there are some limitations that must be considered. These include the fixed position of the bus and circuit breaker, space limitations for current transformers, and the number of auxiliary contacts available on the circuit breaker. Properly considered by the designer when planning an auxiliary layout, these limitations do not preclude the building of an economical and efficient metal-clad switchgear auxiliary line-up.

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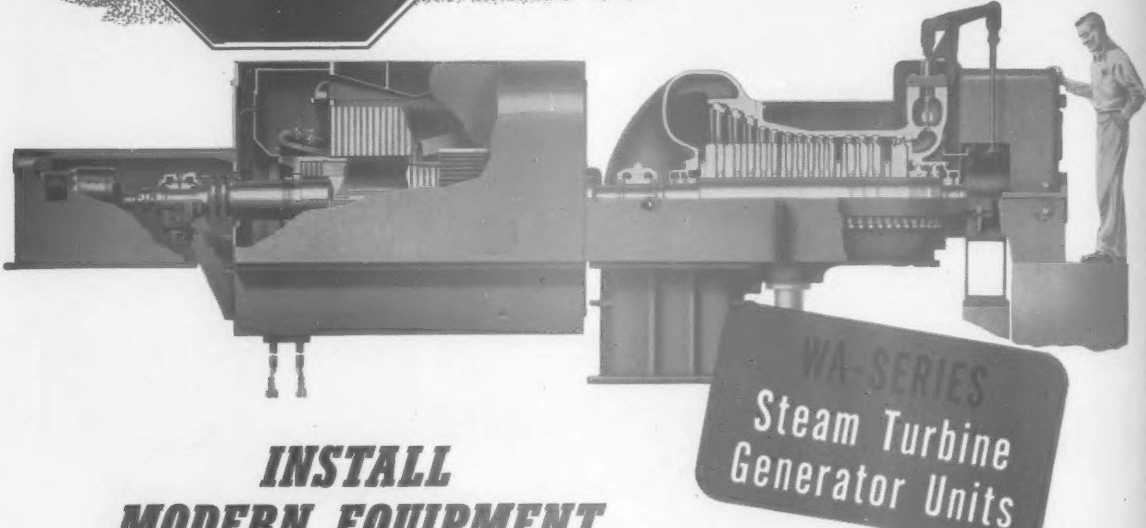

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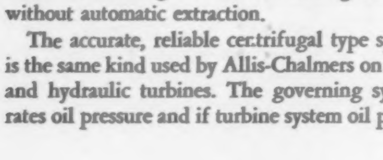

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